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Paleoshorelines, Reefs, and a Rising Sea: South Florida, U.S.A.

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ABSTRACT

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The porous limestone bedrock, thin sediment cover, and tectonic stability of the Florida Platform during the past 15 ka BP provide an exceptionally suitable setting for reconstruction of paleoshorelines and onshore projection of future shorelines in a rising-sea scenario. Paleoshorelines for 8, 6, 4 and 2 ka BP show that (1) a series of limestone islands formed, then drowned, along the outer platform; (2) a distinct trough, called Hawk Channel, separated the outer islands from shore; (3) the lower Keys flooded earlier and more rapidly than the rest of the Keys; and (4) Florida Bay and tidal passes through the middle Keys into the bay developed within the past 4 ka BP.

During the Quaternary, topographic highs were preferential sites for coral growth. Bathed by clear oceanic waters, reefs near the platform flourished. As sea level rose, reefs developed on the platform margin and were gradually displaced to more shoreward bedrock highs. Upon platform flooding, water quality deteriorated and reef luxuriance diminished.

Projection of future shorelines onto land shows that most land forming the Florida Keys would flood in a rise of 1 to 2 m and that a rise of little more than 5 m would submerge all land. Offshore reefs would die, while nearshore reefs would shift landward as the mainland shoreline migrated northward. Onshore topographic highs would become numerous small islands as the Keys flooded, until all drowned. The submerged highs would then become preferred sites for coral growth, until water quality and depth exceeded the optimum for survival.

ADDITIONAL INDEX WORDS: *Florida Keys (USA), Florida reef tract (USA), bedrock topography, paleoshorelines, sea-level rise, Quaternary coral reefs, coral reef distribution, coral growth, storm surge, climatic change, future shorelines.*

INTRODUCTION

At any given time and place, the position of sea level against bedrock topography provides a basis for determination of old shorelines and, with extrapolation, future shorelines. This is particularly true for an area such as south Florida, where the hard limestone bedrock has not been subject to significant erosion or tectonic activity for many thousands of years (ENOS, 1977). This paper focuses on geologic and physiographic changes in the area of the Florida Keys as global sea level rose during the past few thousand years and predicts, in a generalized manner, those changes that would occur in the likely event of a continuing rise. Given the greenhouse scenario, an additional 1.4- to 2.2-cm/yr average eustatic rise of sea level (1.4 to 2.2 m/100 yrs) has been forecast (HOFFMAN *et al.*, 1983). In showing paleoshorelines and future shorelines, this paper attempts to present a timely, relevant, and practical approach to the study of global climatic change.

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Geologic Setting and History

Extensive and continuous limestone deposition has dominated sedimentologic evolution of the south Florida Platform since the early Cretaceous, as shown by penetration to rocks of that age through >5,500 m of carbonate and dolomite during exploratory drilling (APPLIN and APPLIN, 1965; APPLEGATE *et al.*, 1981). These limestones became the bedrock upon which coral reefs thrived for more than 1 Ma during the Pleistocene. The Pleistocene reefs, their reef-derived sands, and skeletal debris from associated marine organisms compose the chain of islands, known as the Florida Keys (Figure 1), that extends along the inner-shelf margin to the south-southwest off the southern

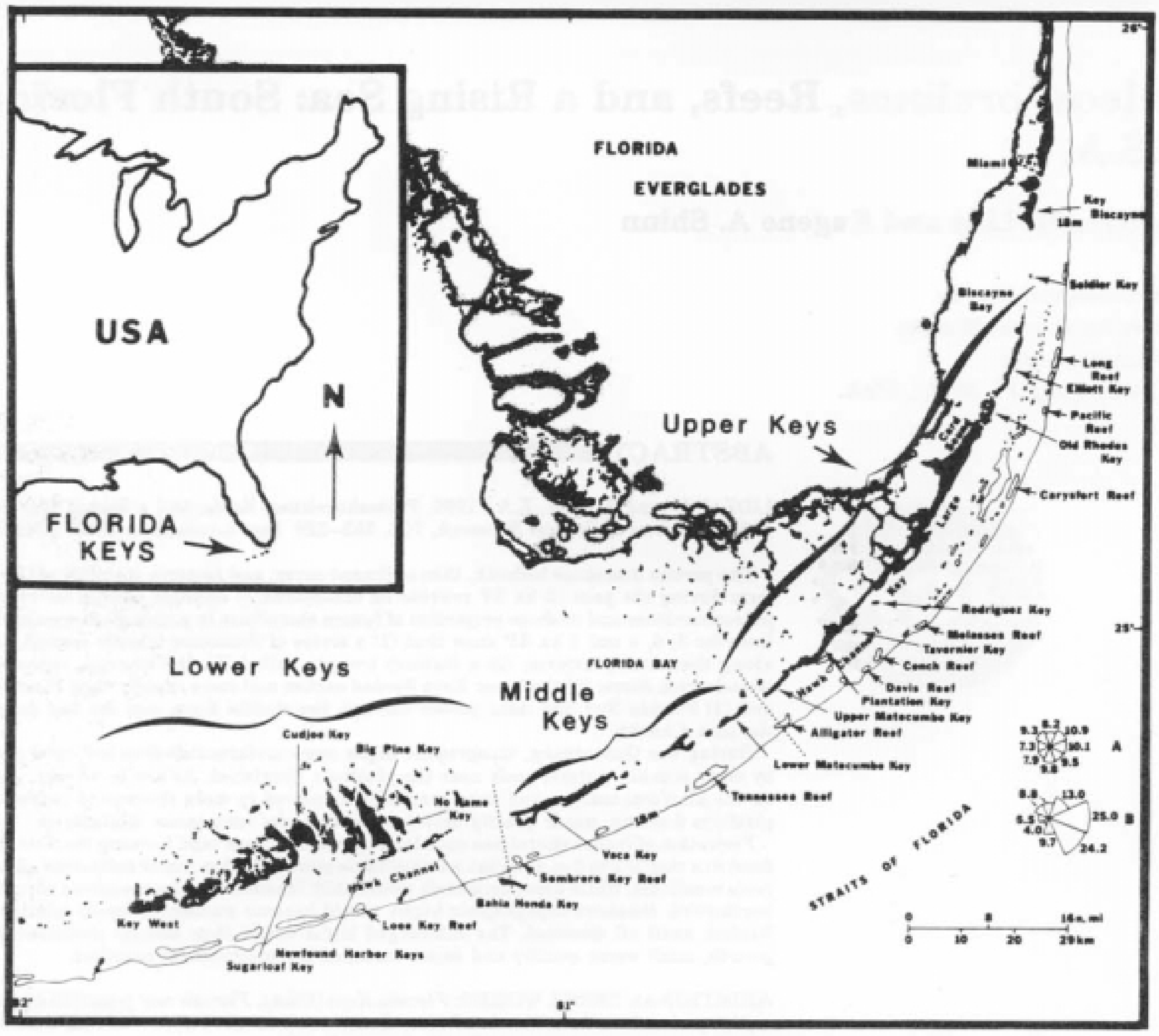

Figure 1. Index map of the Florida Keys and reef tract (inside 18-m contour) showing lower, middle, and upper Keys (bracketed and separated by dotted lines through reef tract). Note width of tidal passes between middle Keys and separating middle from lower Keys. Rose diagram (A) shows mean of average hourly wind velocities; (B) shows percentage of total hours wind blows from each direction.

tip of Florida. Living and dead linear and patch reefs of the Florida reef tract ornament the outer margin of the shallow shelf. Along the outermost edge are drowned Holocene reefs, and seaward of the margin escarpment to the southwest, a chain of multiple, parallel, deep, relict outlier reefs are recognized (LIDZ *et al.*, in press).

The hydrographic regime of the area is controlled by topography and influenced by an admixture of clear, open-ocean water of the Florida Current (Gulf Stream) with sediment-laden, turbid, cold (winter) waters from lagoonal Florida Bay and the Gulf of Mexico. Antecedent topography, water quality, and water depth, the latter two being sea-level dependent, are the primary influences that have determined distribution and development of both ancient and modern coral reefs in the area (SHINN *et al.*, 1989).

Inshore of the reef tract (Figure 1), the chain of islands forming the Florida Keys is divided on the basis of environmental conditions into three major groups from southwest to northeast: the lower Keys, middle Keys, and upper Keys. Seaward of the Keys along the reef tract, the major physiographic differences occur off the middle Keys, where reefs are sparse and relatively senescent, carbonate sands are abundant, and large, deep tidal passes separate the islands. The bedrock trough (Hawk Channel) landward of the reefs is deeper by several meters off the lower Keys than off the middle and upper Keys, and the shape and composition of the islands of the lower Keys differ from those of the middle and upper Keys. The lower Keys are oriented north-south, rather than east-west, and are composed of oolite rather than coralline limestone. These islands have been interpreted as preserved tidal-bar deposits (HOFFMEISTER *et al.*, 1967). Contour maps of the Miami Oolite (SANFORD, 1909), which forms the landmass upon which the city of Miami is built, reveal distinct tidal-bar morphology similar to that of the lower Keys (HOFFMEISTER, 1974; HALLEY *et al.*, 1977). Although there are numerous tidal passes between the lower Keys, the water is shallow, and both circulation and volume of water exchange through the passes are considerably less than in the middle Keys. These differences become particularly evident as paleoshorelines are charted.

The region of south Florida has been undergoing depositional thickening to the south and west since the Upper Jurassic (APPLEGATE *et al.*, 1981). Topography in the east part of Florida is higher than to the west, which led PARKER and COOKE (1944) and PARKER *et al.* (1955) to infer that westward tilting of the Florida Platform took place during the Pliocene and early Pleistocene. Westward tilt is further substantiated by the low elevation of the Key West Oolite in the lower Florida Keys relative to that of the Miami Oolite to the north; the Key West Oolite is believed to have been deposited at the same sea level as the higher elevation Miami Oolite (HOFFMEISTER, 1974). Other evidence of a westward tilt includes a linear Pleistocene beach deposit in the lower Keys that dips along strike to the west (SHINN *et al.*, 1989) and general thickening of the Pleistocene section to the west (PERKINS, 1977).

Evidence of Pleistocene sea-level rises and falls in the south Florida-Bahamas region consists of subsurface subaerial features, such as laminated calcrete (also called caliche or soilstone), and peat, root casts, and molds. Calcrete, a rusty brown, strongly indurated lamellar crust composed of calcite often containing aluminum silicates, is formed by the leaching and reprecipitation of calcium carbonate under the influence of humic-soil solutions on an exposed surface covered by peaty soil. The aluminum silicates, mainly derived from Saharan dust (MUHS *et al.*, 1990), are incorporated during the slow process of calcrete formation. The crusts form millimeter-scale laminations by upward accretion, as demonstrated by ^{14}C dating of individual laminae (ROBBIN and STIPP, 1979), and are several centimeters thick. Calcrete often contains blackened, angular limestone pebbles thought to have been darkened by forest fires (SHINN and LIDZ, 1988). PERKINS (1977) described the record of five sea-level falls in south Florida by correlation of five major calcrete-coated unconformities. BEACH and GINSBURG (1980) identified at least 18 horizons of subaerial exposure within the Pleistocene section on the Great Bahama Bank. Radiocarbon dating of peat and soilstone crusts beneath Alligator and Davis Reefs (Figure 1) showed that the limestone on which Alligator Reef formed was above sea level at approximately 7.3 ka BP and the rock under Davis Reef was exposed between 13.7 and 6.8 ka BP (ROBBIN, 1981).

Local sea level may also be influenced by subsidence. Given that much of the coast of the United States is sinking, the relative sea-level rise at a particular location undergoing isostatic subsidence will generally be greater than predicted levels.

Sea-level curves for south Florida were constructed by SCHOLL *et al.* (1969, and references therein), STOCKMAN *et al.* (1967), and FAIRBRIDGE (1974) on the basis of ^{14}C dating of terrestrial and mangrove peats now below sea level in Florida Bay. ROBBIN (1984) integrated data from these curves with ^{14}C ages of continuous peat sections exposed in the banks of tidal passes through the Florida Keys, peats beneath coral reefs, and subaerially formed, laminated soilstone crusts collected from 0 to 9.2 m below sea level along the reef tract (Figure 2). The curve of ROBBIN (1984) is considered, therefore, the most relevant to reef development in south Florida because it is based on data closer to and, in some cases, beneath the reefs. The older part of the curve of ROBBIN (1984) has been modified here to accommodate well-known worldwide evidence that sea level at 15 ka BP was >100 m lower than today (MILLIMAN and EMERY, 1968; VAIL *et al.*, 1977; HAQ *et al.*, 1987; FAIRBANKS, 1989; WILGUS *et al.*, 1989, among many others). Although dates for paleoshorelines before 8 ka BP are not exact, our major conclusions remain unaffected

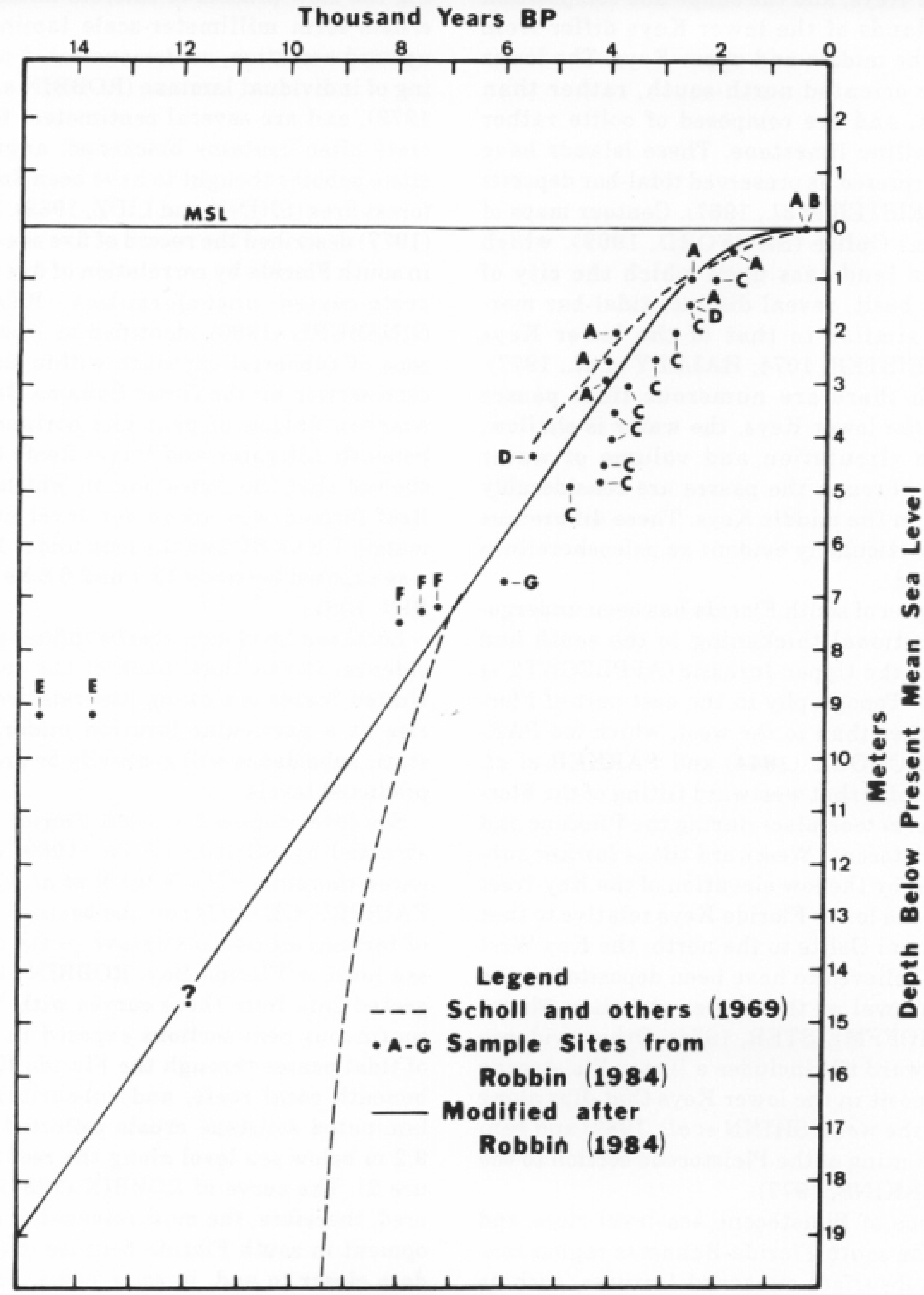

Figure 2. Sea-level curve modified after Robbin (1984). Dashed portion of curve older than 8 ka BP probably represents the more likely rate of rise. Data for 8 ka BP to the present are considered reliable. Sample sites and materials A–G: (A) Sands Cut, mangrove peat; (B) Elliott Key, soilstone crust; (C) Broad Creek, mangrove peat; (D) Rodriguez Key, mangrove peat; (E) Davis Reef, soilstone crust; (F) Alligator Reef, soilstone crust and mangrove peat; (G) The Quicksands (approximately 16 km west-southwest of the Marquesas Keys, located due west of Key West), mangrove peat. Current rate of rise (38 cm/100 yrs) in Florida Keys is shown in Figure 5.

because the shoreline positions against the porous limestone bedrock within the general period before 8 ka BP had to have existed. Data from the past 8 ka BP (ROBBIN, 1984) indicate that sea level has risen an average of 11 cm/100 yrs in the Florida Keys. Tide gauges along the Atlantic and Gulf coasts, however, have recorded a dramatic increase in relative sea-level rise over the last 58 years (WANLESS, 1989). For Key West, the rate is equivalent to about 38 cm/100 yrs.

The Florida Reef Tract

Most living reefs are located opposite the larger islands of Key Largo and the lower Keys, which act as barriers between the reefs and the turbid waters of Florida Bay. These reefs are composed principally of the temperature-sensitive, rapidly growing branching corals *Acropora palmata* and *A. cervicornis* and massive corals such as *Montastraea annularis* and *Diploria strigosa* (PORTER *et al.*, 1982; ROBERTS *et al.*, 1982; JAAP, 1984; SHINN, 1984). On the other hand, relatively senescent reefs are located opposite tidal passes and are poorly developed, lack the major reef-building corals, and harbor only the hardier, slower growing species, such as the encrusting stinging coral *Millepora complanata*. Exposures created recently by ship groundings and core drilling (SHINN, 1963; SHINN *et al.*, 1981; ROBBIN, 1984) show that the major constructor of the large Holocene reefs was *Acropora palmata*, the species presently building reefs elsewhere throughout the Caribbean. Radiocarbon dating of *A. palmata* from the upper and lower Keys (*i.e.*, Molasses, Alligator, and Looe Key Reefs) indicates they flourished from 4 to 2 ka BP (ROBBIN, 1981; SHINN *et al.*, 1981). These data suggest that before 4 ka BP, and before Florida Bay reached its present state of development, coral reefs flourished over and around pre-existing topographic highs and along the elevated rim of the platform margin.

METHODS

The regional base maps used to reconstruct the positions of paleoshorelines shown in Figure 3A–F are from ENOS (1977), who used a high-resolution subbottom sparker profiler to contour the underlying Pleistocene bedrock surface. Radiocarbon dates of corals recovered from cores and excavations in Holocene reefs (LIGHTY, 1977; SHINN *et al.*, 1977; SHINN, 1980; SHINN *et al.*, 1981) complement the sea-level curve of ROBBIN (1984; Figure 2), which was used to interpret relative ages of the paleoshorelines. Because the islands of the Florida Keys are composed of the same thinly veneered (soil cover on calcrete) Pleistocene limestone that underlies the offshore reefs, onshore topographic contours provide a method by which the positions of future shorelines can be predicted and the areas where new coral reefs are most likely to become established can be identified. Base maps used for future local shorelines (Figure 4A–J) are U.S. Geological Survey topographic quadrangles (scale 1:24,000). On all the maps in Figures 3 and 4, as the sea advances onshore, its earlier interpreted positions are indicated by dotted lines.

Several assumptions were made in reconstruction of the paleoshorelines and development of future strandlines. (1) Sea level rise would exceed sediment production and island growth. (2) There would be little, if any, sediment on the limestone surface prior to flooding. Sediment and soil are usually thin or absent on Pleistocene rock highs throughout south Florida and the Caribbean. However, there may be 1 to 2 m of sediment and peat in topographic lows such as those in the Everglades (Figure 1). (3) Erosion of the limestone bedrock would be insignificant. (4) Subsidence would be minimal.

Interpretation of paleoshoreline positions in conjunction with data from the sea-level curve allows approximation of the locations of two of the many shorelines that existed before 8 ka BP and more accurate positioning of those at 8, 6, 4, and 2 ka BP (Figure 3). The two earliest paleoshorelines depicted are probably not correctly dated because of the lack of accurate local ^{14}C data from before 8 ka BP. The ages are not important, however; the paleoshorelines depicted existed at some time before 8 ka BP. Ages of the more recent paleoshorelines shown are considered more precise. All depths are reported as meters below sea level. Although tidal fluctuation is less than 1 m, seismic data upon which the paleoshoreline maps are based (ENOS, 1977) were corrected to mean sea level.

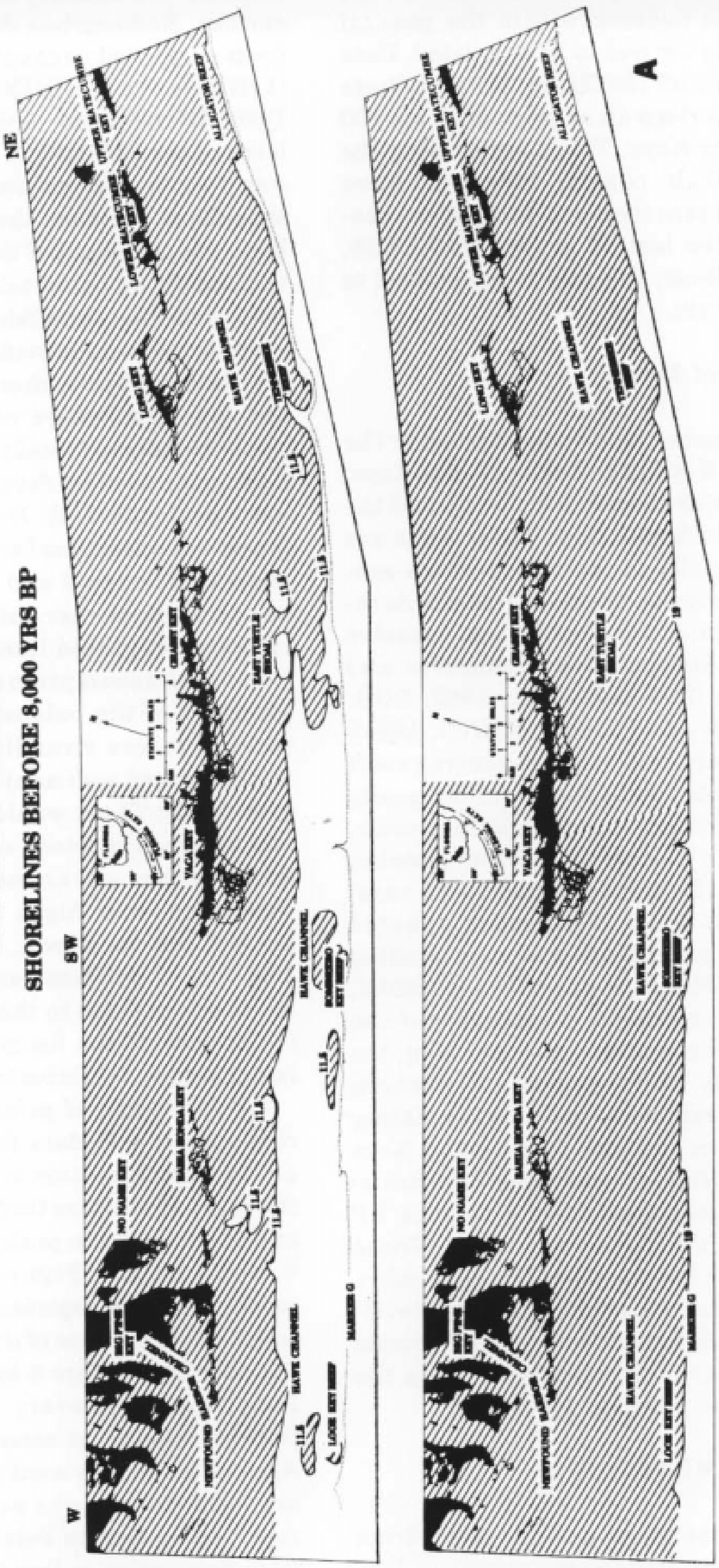

Figure 3. Paleoshorelines in the Florida Keys. Pattern—land; white—seawater; black—Florida Keys as they exist today. (A). Two positions of sea level in the lower and middle Keys before 8 ka BP. Note change from linear to irregular paleostrandline and development of limestone islands and saline ponds as the sea rose. Also note portion of Hawk Channel in this area is topographically lower than to the northeast (shown in B) and became partially flooded some time before 8 ka BP.

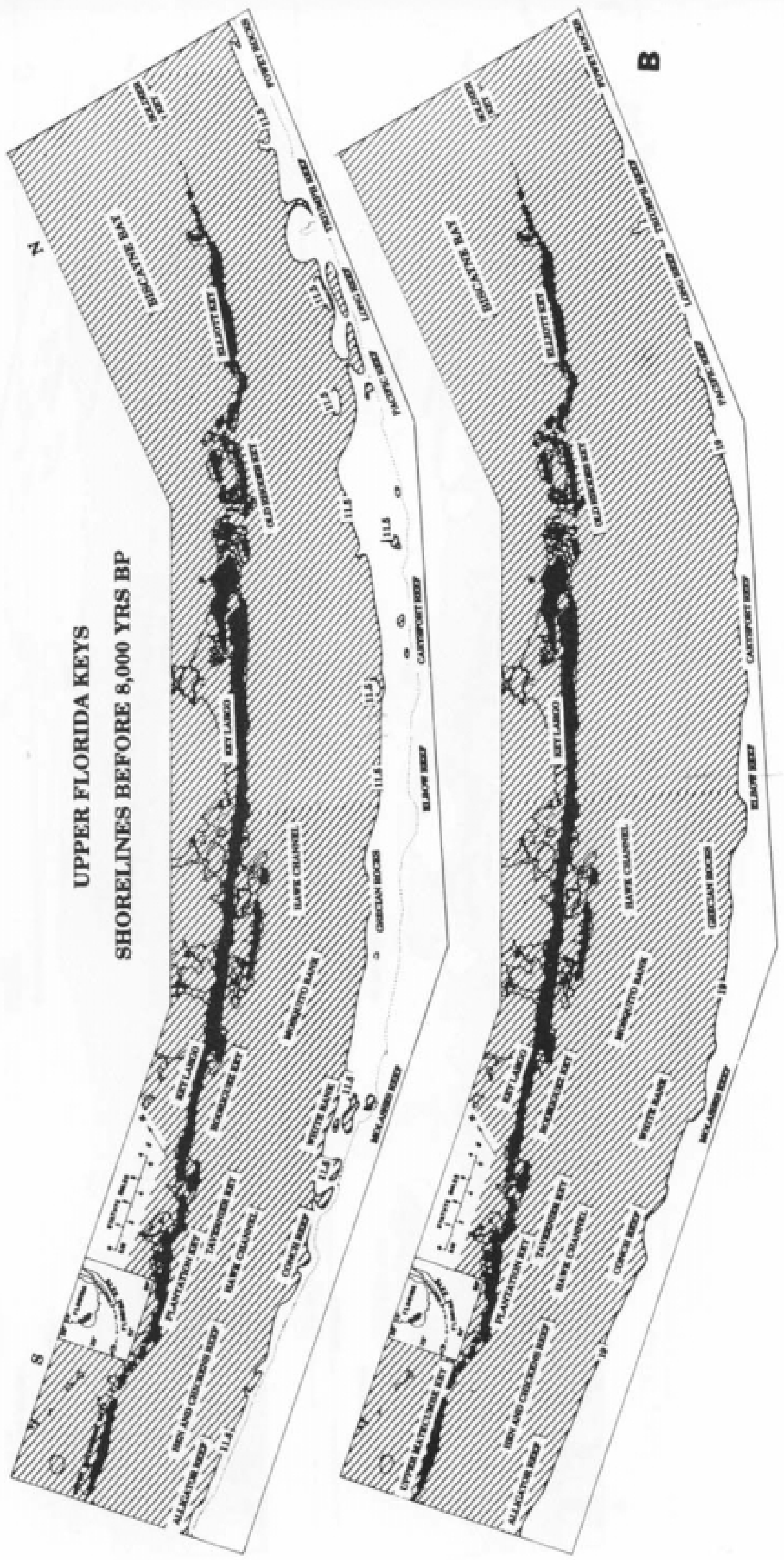

Figure 3 Cont. (B) Two positions of sea level in the upper Keys before 8 ka BP. Note portion of Hawk Channel in this area was land.

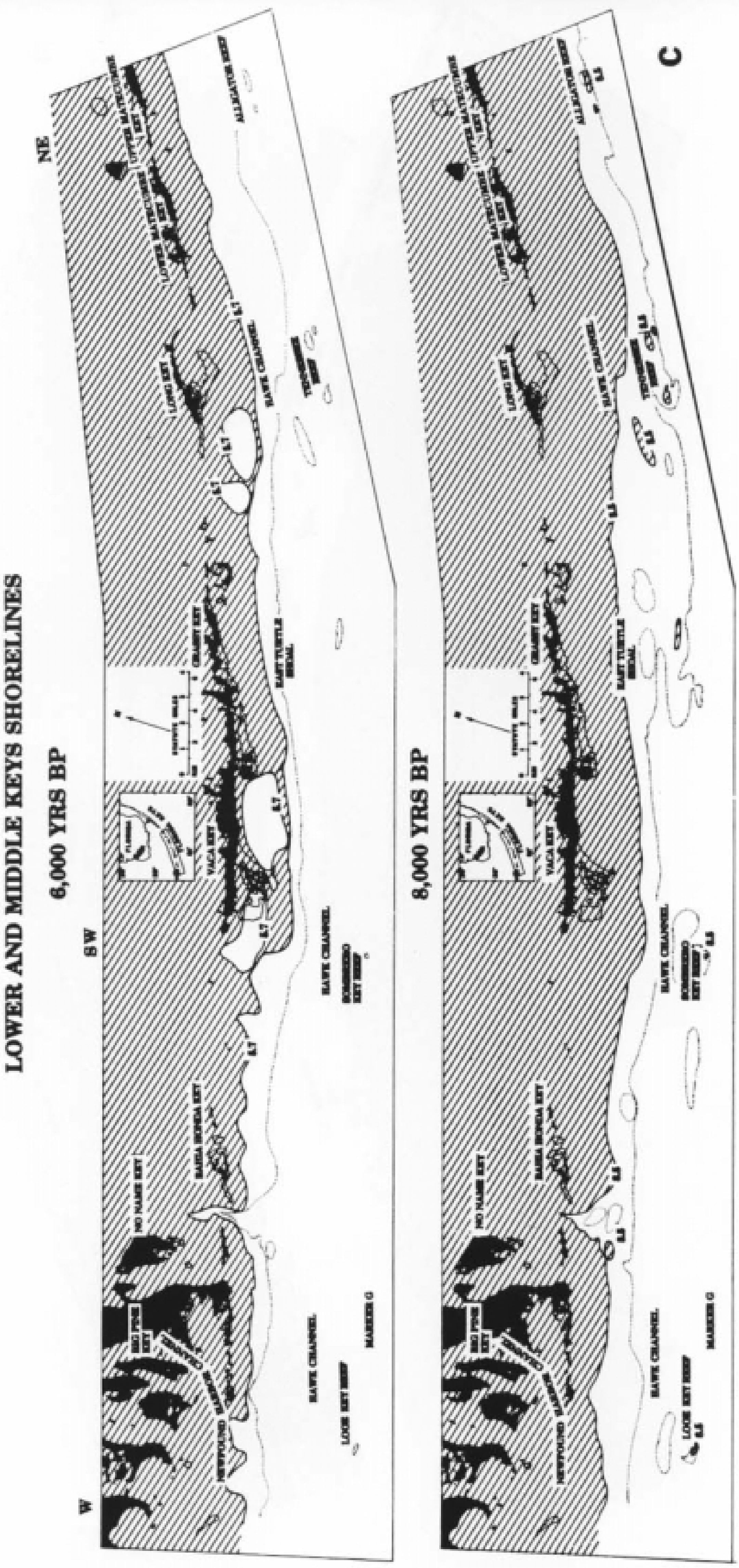

Figure 3 Cont. (C) Paleoshorelines in the lower and middle Keys at 8 and 6 ka BP. Note earlier paleostrandline position shown at top in (A), indicated by dotted line, and drowned islands. Also note finger of sea extending landward, the beginning of Bahia Honda Channel, and development of onshore lagoons by 6 ka BP.

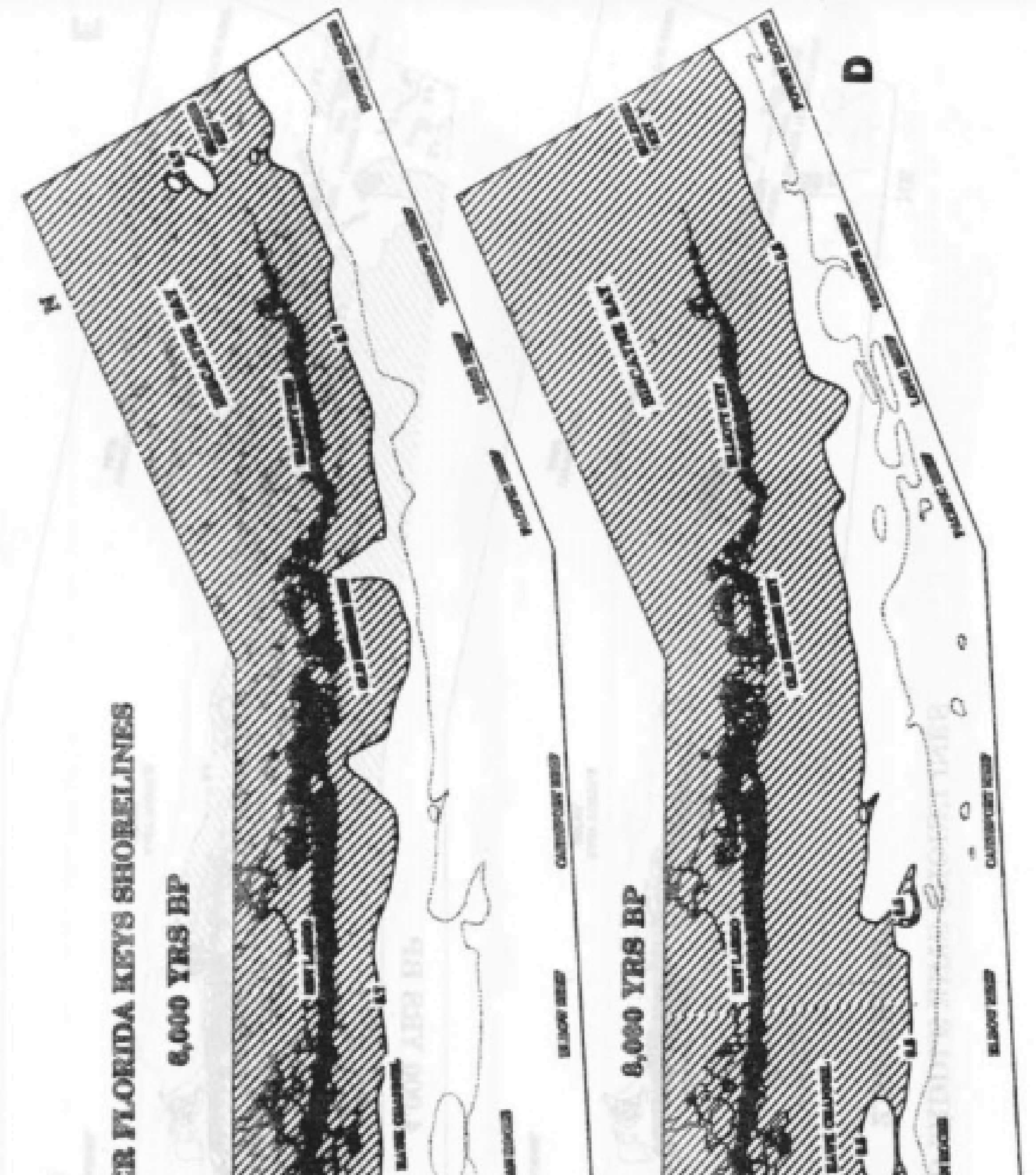

Figure 3 Cont. (D) Paleoshorelines in the upper Keys at 8 and 6 ka BP. Note tongue of water filling Hawk Channel area between Mosquito and White Banks at 8 ka BP. (C) and (D) show Hawk Channel became fully flooded by 6 ka BP.

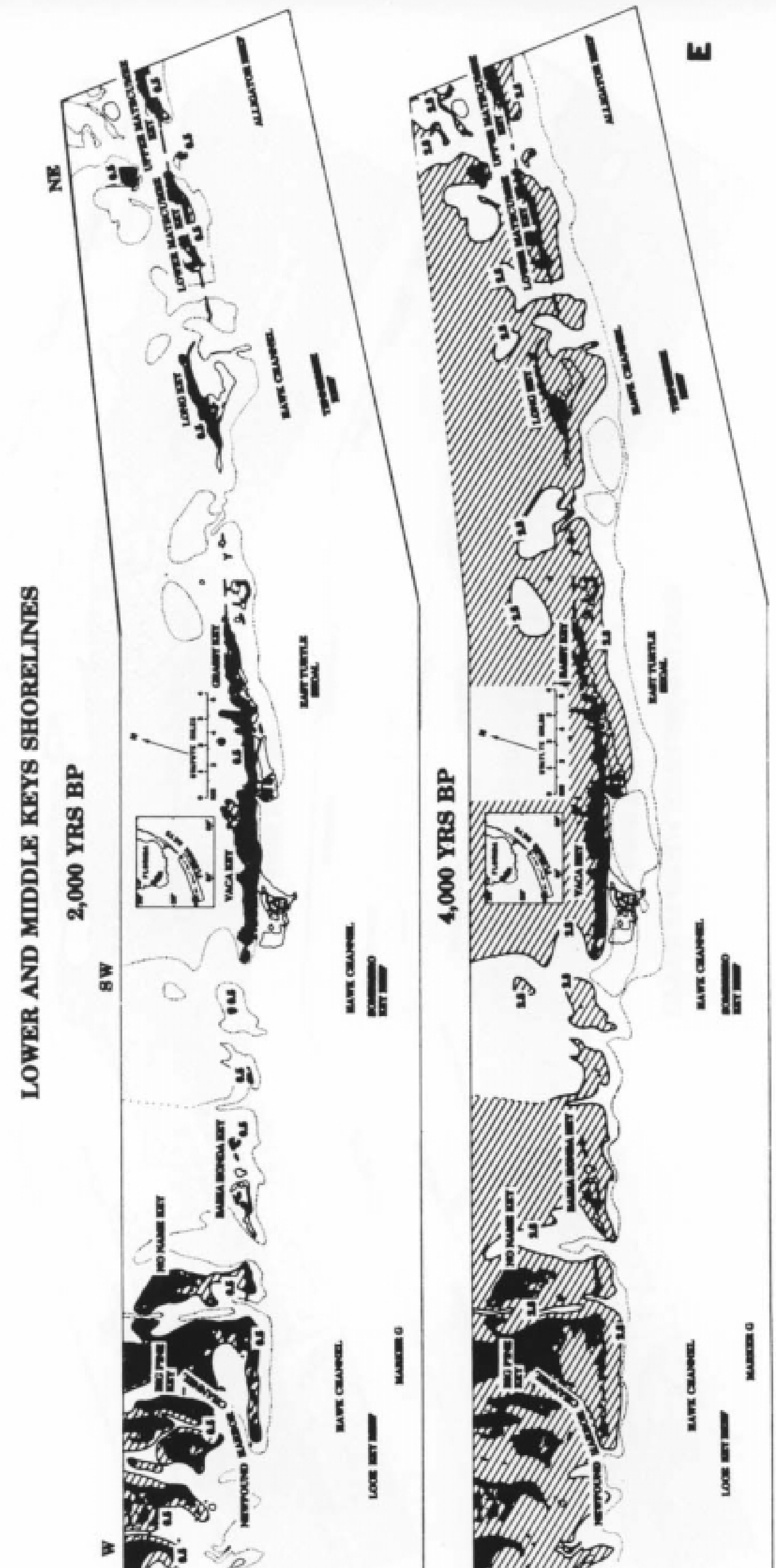

Figure 3 Cont. (E) Paleoshorelines in the lower and middle Keys at 4 and 2 ka BP. Note flooding of tidal passes through the middle Keys and encroachment of the sea into topographic low that would become Florida Bay (northwest of Sombrero Key and north of Upper Matecumbe Key). By 2 ka, the shoreline looked quite similar to that of today.

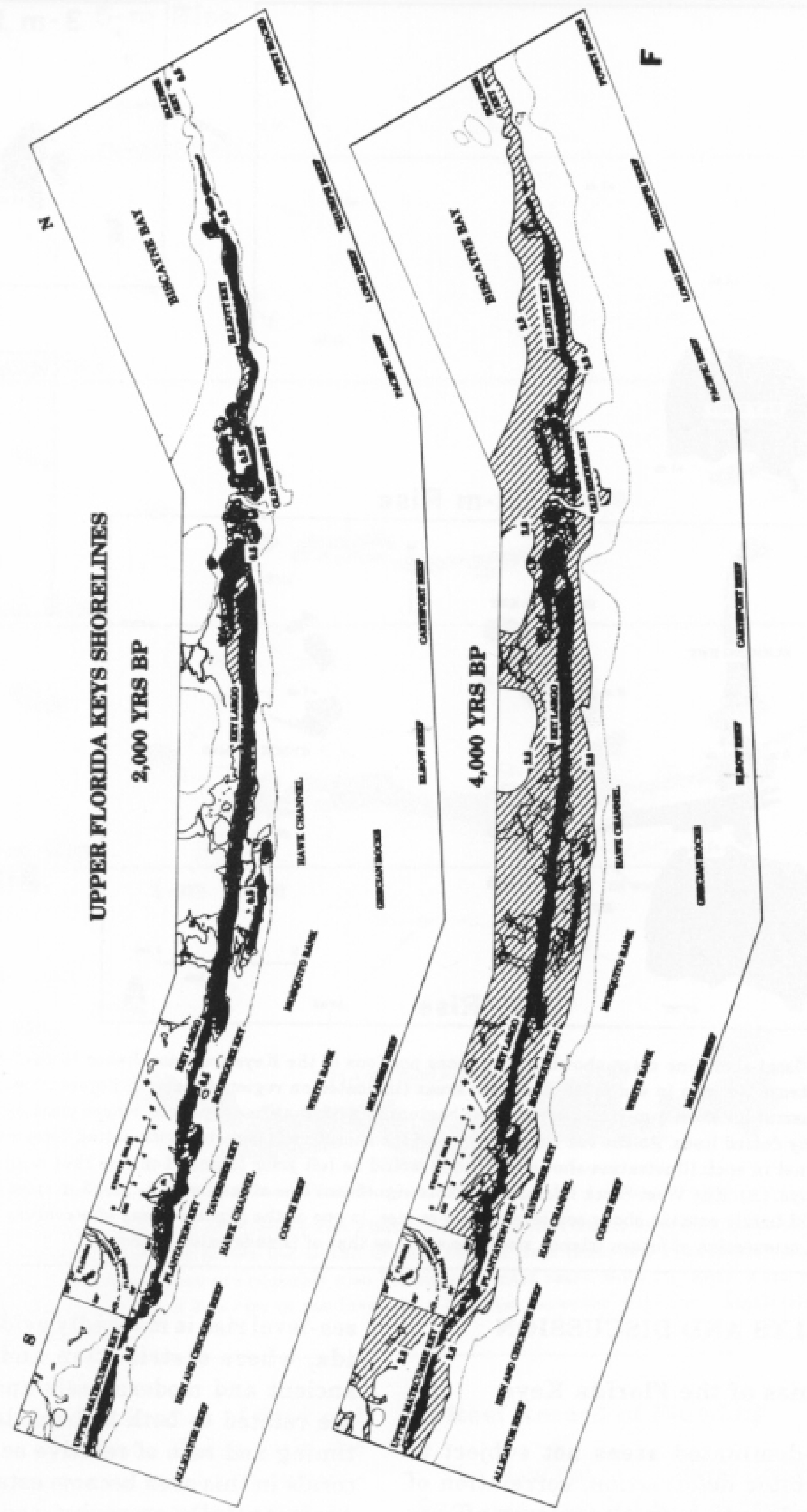

Figure 3 Cont. (F) Paleoshorelines in the upper Keys at 4 and 2 ka BP. Note flooding of Biscayne Bay bedrock depression by 4 ka BP and extensive linear feature, composed of Pleistocene Key Largo Limestone, that would form the upper Florida Keys.

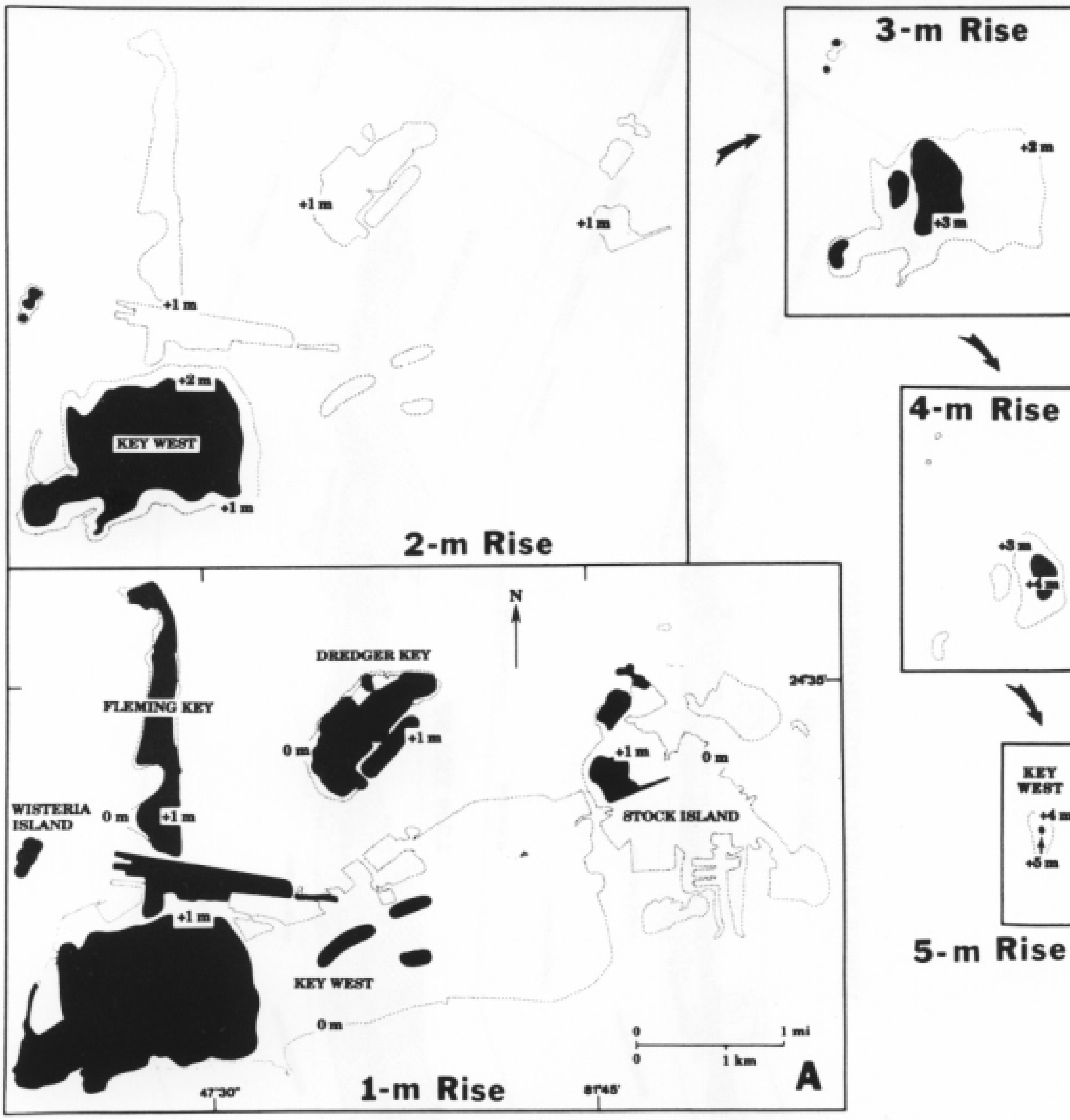

Figure 4. Future local-shoreline maps showing only those portions of the Keys from southwest to northeast where land would remain exposed after a 1-m rise in sea level. All other areas (indicated on regional maps in Figure 3) would flood in a 1-m rise. Panels in each illustration show 1-m incremental rises beginning with lowermost panels, where position of present sea level (0 m) is represented by dotted lines. As the sea rises, each previous shoreline is depicted with dotted lines and exposed land (black) decreases. Last panel in each illustration shows what land would be left prior to final 1-m rise that would submerge all land in that area of the Keys. (A). Key West-Stock Island area. Note significant loss of land with 1- and 2-m rises in sea level. Key West, part of which would barely remain above sea level at a 5-m rise, is one of the highest areas of elevation in the Keys. Also note general shape and orientation of future islands would be same as that of islands existing today.

RESULTS AND DISCUSSION

Paleoshorelines of the Florida Keys

In bedrock-dominated areas not subject to erosion or tectonic deformation, correlation of former sea levels with bedrock contours affords a relatively accurate method of locating paleoshorelines. The relation between antecedent Pleistocene bedrock topography and Holocene sea-level rise is markedly evident in south Florida, where distribution and development of ancient and modern reefs and sediment facies are related to both bedrock landscape and the timing and rate of relative sea-level rise. Most corals in this area became established and grew preferentially on rocky, sediment-free topographic highs; only with great difficulty do corals recruit to surrounding sediment-filled lows (SHINN *et al.*, 1989). Thus, the location of bur-

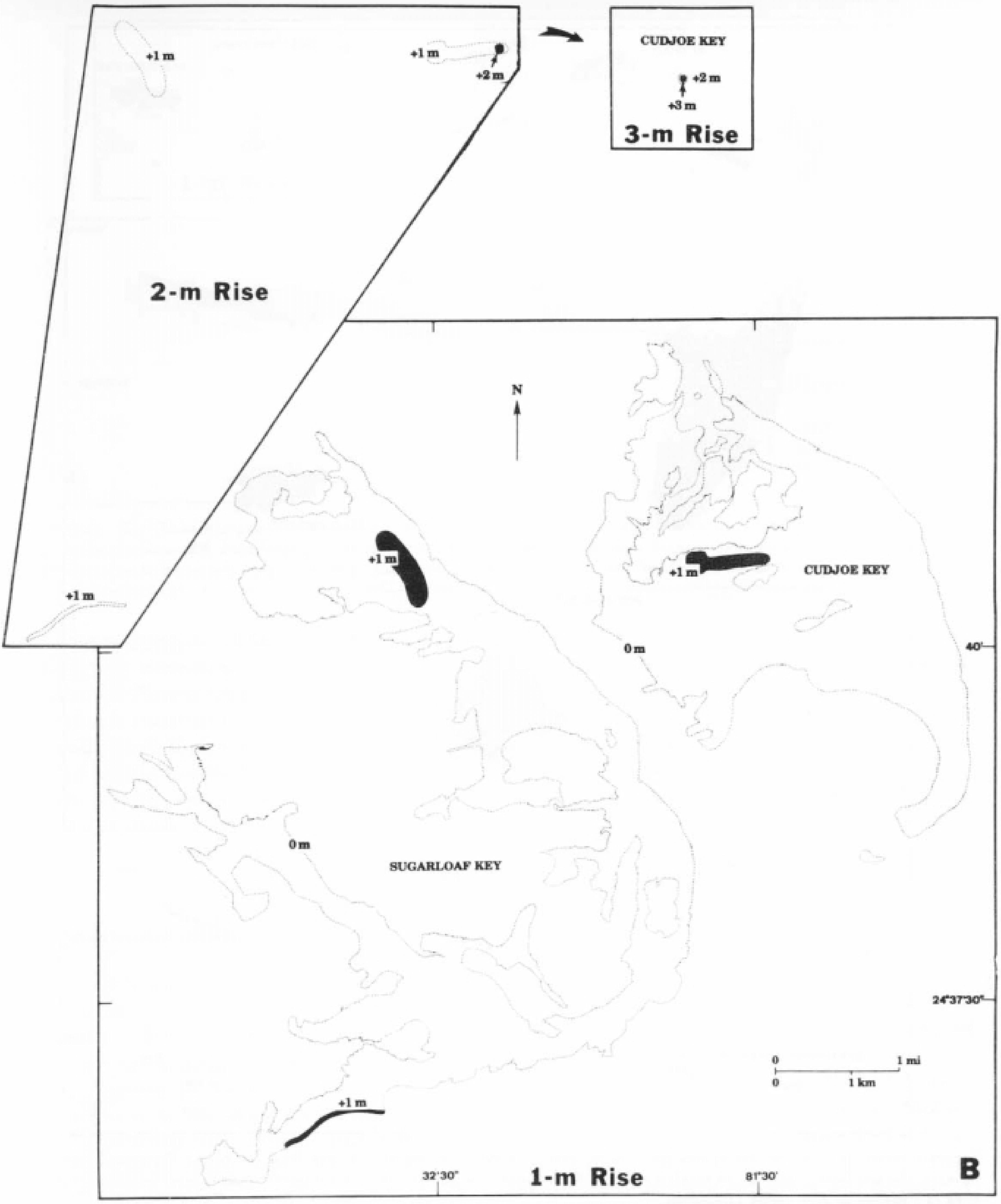

Figure 4 Cont. (B). Sugarloaf and Cudjoe Keys showing extensive land loss after a 1-m rise in sea level. A 2-m rise would flood two of the three islands formed earlier; a 3-m rise would leave a dot of land at Cudjoe Key.

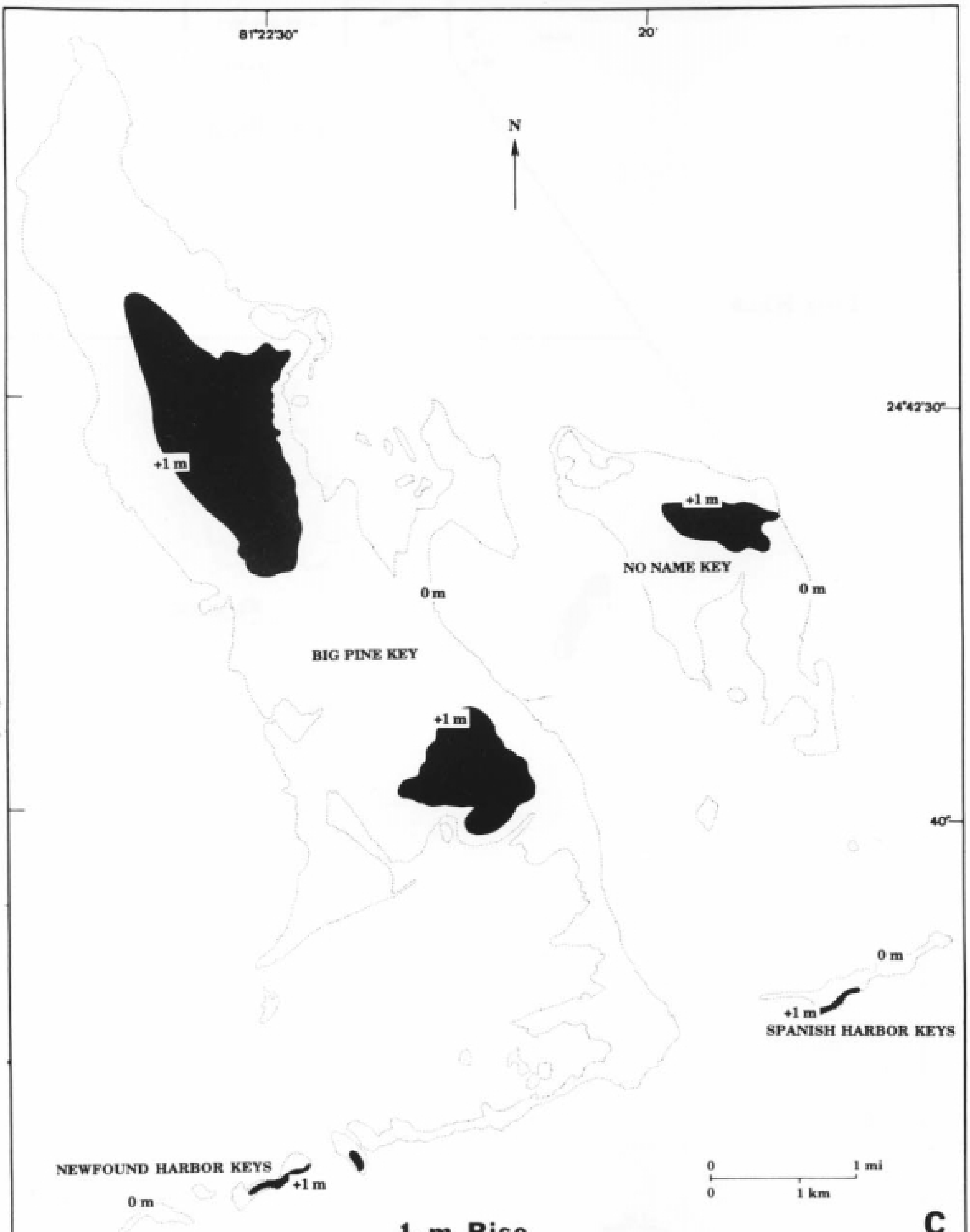

Figure 4 Cont. (C). A 1-m rise in sea level would greatly reduce exposed land at Big Pine, No Name, Newfound Harbor, and Spanish Harbor Keys, creating six smaller islands. Note shape of southernmost islands corresponds to east-west linearity in this area of Pleistocene Key Largo Limestone.

ied topographic highs helps explain the location of Quaternary reefs. This knowledge furnishes data by which paleoshorelines can be traced as the Holocene sea progressively transgressed the Pleistocene surface.

Sometime before 8 ka BP, the relatively smooth coastline along the Florida Keys

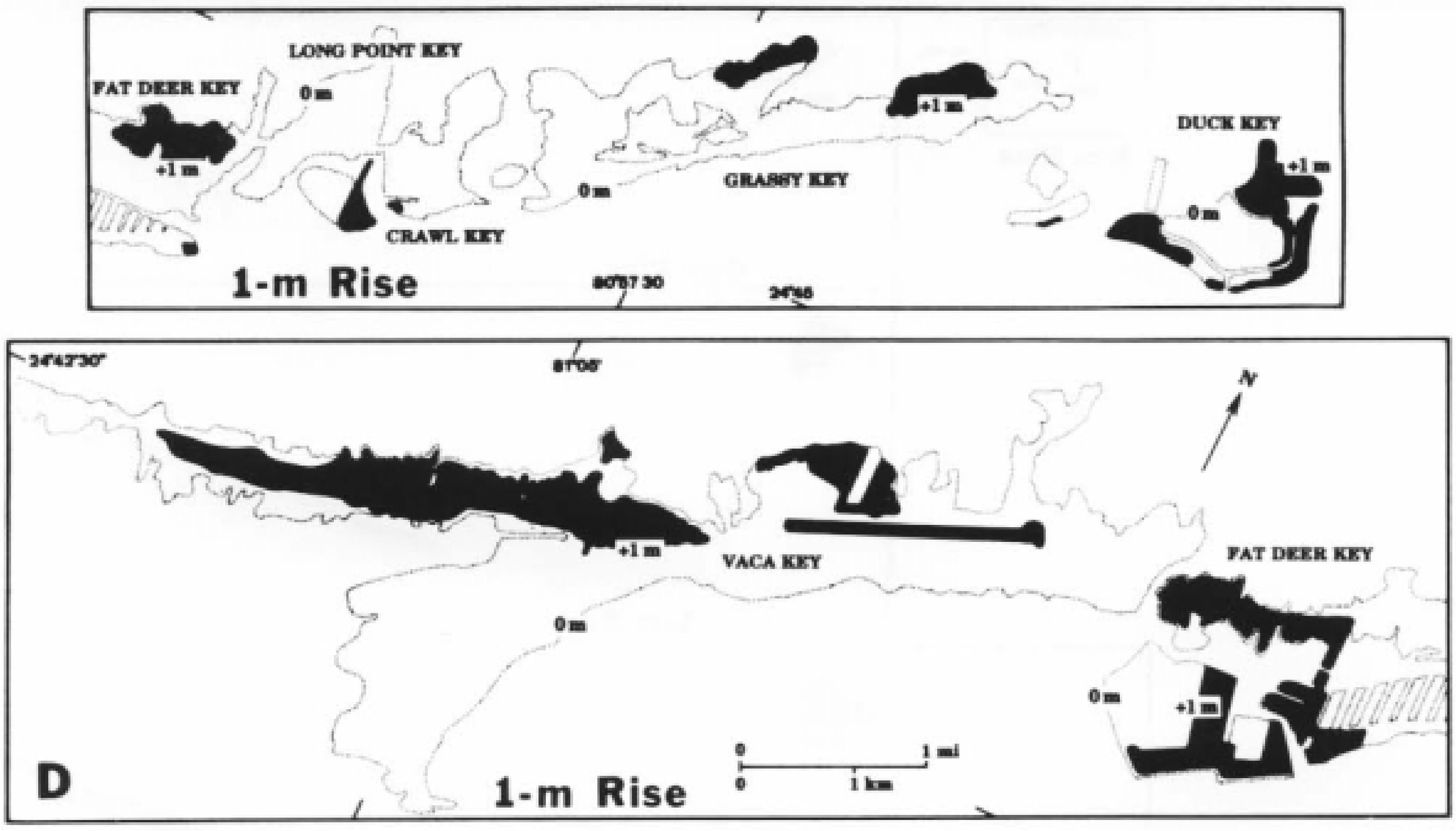

Figure 4 Cont. (D). These two panels show contiguous land area, rather than graduated sea-level rise, and indicate the effects of a 1-m sea-level rise on the Vaca-Grassy Keys area (middle Keys). A 2-m rise would flood all land here. Elongate area in right center of Vaca Key is Marathon Airport runway. Also note man-made angular land features on Fat Deer Key.

became more irregular (Figure 3A, B). Numerous limestone islands were created as the sea rose around Pleistocene topographic highs. These islands eventually drowned with continued rise. Bedrock highs became islands at Sombrero Key off the middle Keys, and at Molasses, Carysfort, Pacific, and Long Reefs off the upper Keys. Saline ponds formed as the land flooded. The south-southwestern and deepest part of Hawk Channel in the Florida Keys, in the vicinity of Looe Key, was submerged.

By 8 ka BP, islands existed at Tennessee and Alligator Reefs off the middle Keys and at Conch Reef off the upper Keys (Figure 3C, D). Only a vestige of land was left exposed at Looe and Sombrero Keys. A large tongue of water began to encroach landward into the north part of Hawk Channel in the area of Tavernier and Rodriguez Keys in the upper Keys, and a small inlet formed south and west of Bahia Honda Key in the lower Keys. Sea level was 8.5 m below present, and the shoreline ranged from approximately 3 to 6 km offshore from what is land today. By 6 ka BP, the shoreline was still only mildly irregular, but lagoons began to form on land. Hawk Channel was fully formed, and in it water flowed freely along the length of the reef tract. Its flooding probably had ecologic effects on certain coral reefs similar to those caused later by the creation of Florida and Biscayne Bays. The deleterious effect of inimical backreef lagoonal waters created by the rising sea has been demonstrated in many parts of the world (NEUMANN and MACINTYRE, 1985). All previously exposed islands along the reef tract were submerged, and the first breach of water through what would become the chain of Keys occurred to the west of Bahia Honda Key. In the area of the upper Keys, inlets of water approached either side of Old Rhodes Key, and ponds formed west of Soldier Key. Sea level was 5.7 m lower than today.

Sea level at 4 ka BP was approximately 3 m lower than today (Figure 3E, F) and the rate of eustatic rise, although continual, had begun to decrease (NEUMANN, 1971; FAIRBANKS, 1989). Under such conditions, most of Florida Bay and many of the tidal passes through the Florida Keys did not exist. Water quality along the platform margin, where it was bathed by the Florida Current, was more favorable for coral growth than today. Irregularity of the south Florida coastline increased dramatically at this time as water flowed from Hawk Channel through the numerous depressions between onshore topographic highs and covered the low-

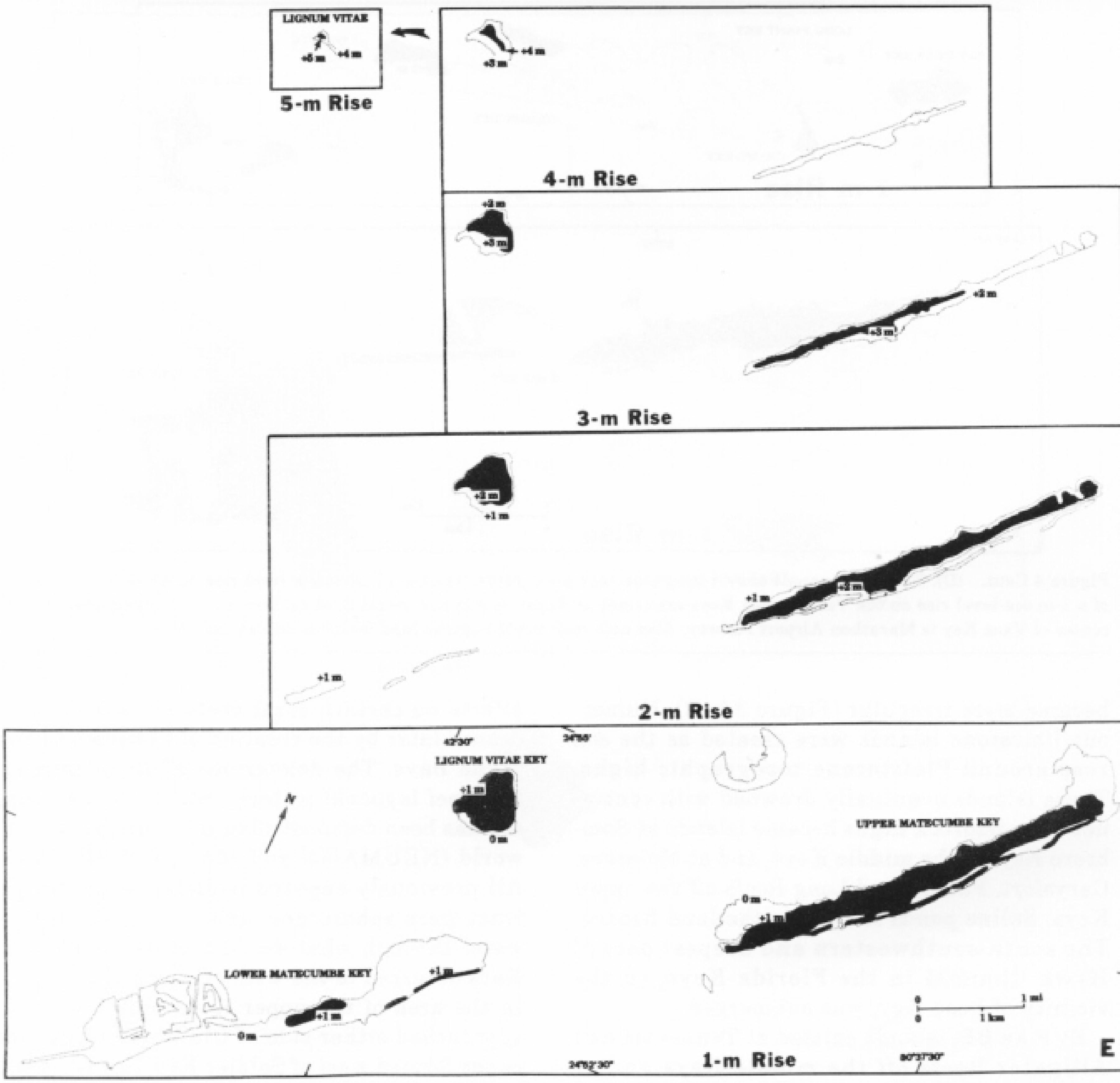

Figure 4 Cont. (E). Lower Matecumbe Key (lower Keys) would flood rapidly in a 1-m rise in sea level, whereas Lignum Vitae (middle Keys) and Upper Matecumbe Keys (upper Keys) would flood more gradually. Note linear (beach berm) features on seaward sides of the Matecumbes. At a 5-m rise, all land would drown except a small island at Lignum Vitae Key.

lying areas to the north and west. A few islands formed in the area of the lower and middle Keys. Florida Bay began to form in the area north of and between Vaca and Bahia Honda Keys and Biscayne Bay was flooded. At 2.8 m below present sea level, the seaward edge of the shoreline ranged from 1 to 4 km from the present shoreline. By 2 ka BP, the shorelines of the Florida Keys and Florida Bay were similar to those of today. Virtually all topographic lows were flooded, as was the area of Florida Bay. Biscayne Bay increased in size. As sea level continued to rise to near-present conditions, inimical waters from Florida Bay in the vicinity of the middle Keys and from Biscayne Bay to the north slowly killed the principal, faster growing reef builders. Sea level was 0.5 m lower than today. Because of the influx of lagoonal water and increasing water depths, this final phase of flooding had the most pronounced

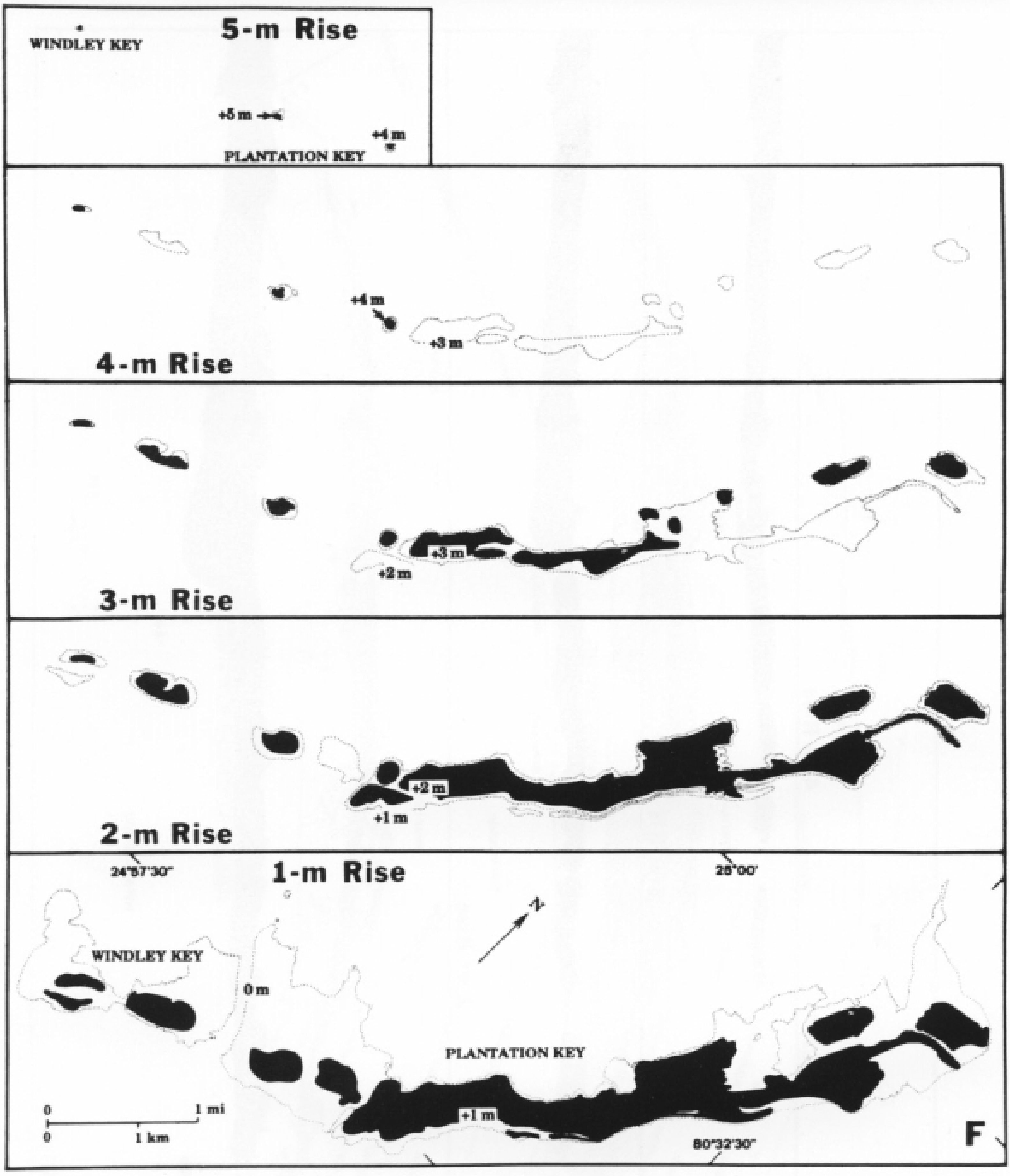

Figure 4 Cont. (F). A 1-m rise in sea level at Windley and Plantation Keys would create numerous smaller islands. Quarrying of coralline limestone at Windley Key has shown the island to have formed from luxuriant Pleistocene patch reefs of massive corals. Two small islands on Plantation Key are probably also Pleistocene patch reefs. Note this area is one of the highest, with considerable land remaining until after a 3-m rise in sea level. At a 5-m rise, however, only three small islands would remain that would drown in the next 1-m rise.

effect on the eventual distribution of dead and living reefs on the reef tract. Today, only the more hardy, slower growing species of massive corals and non-reef-building gorgonians, sea fans, and *Millepora complanata* survive on the senescent reefs off the middle Keys.

A Reef Record of Flooding

The slow but progressive flooding of the platform was recorded by the reefs. Indeed, many elements of the reef tract ecosystem became significantly altered and preserved as sea level

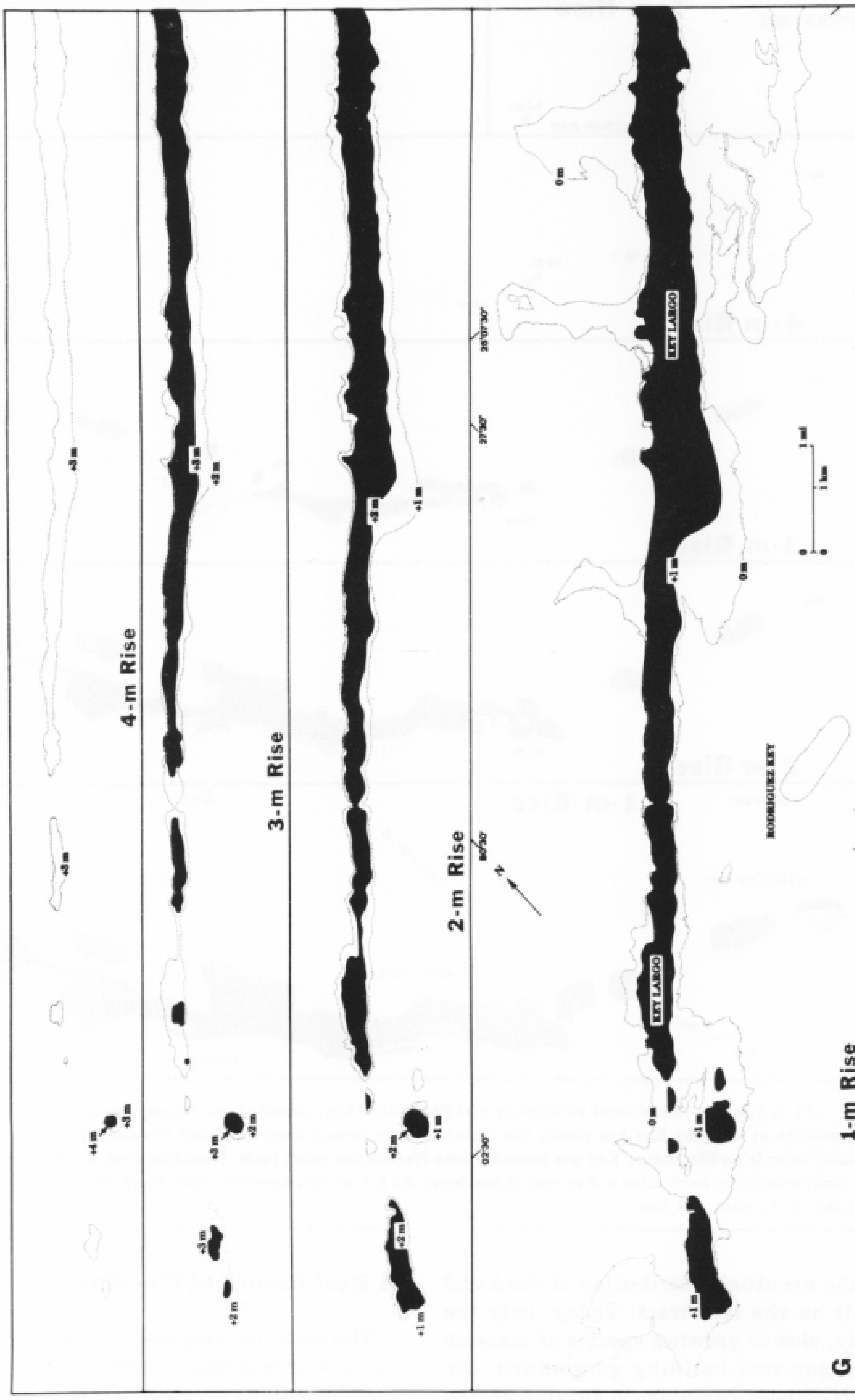

Figure 4 Cont. (G). Lower Key Largo would quickly become a streamlined linear island after a 1-m rise in sea level, with several small islands formed at the south tip (probably Pleistocene patch reefs). The island would then flood more gradually until only a single subcircular island remained at a 4-m rise in sea level.

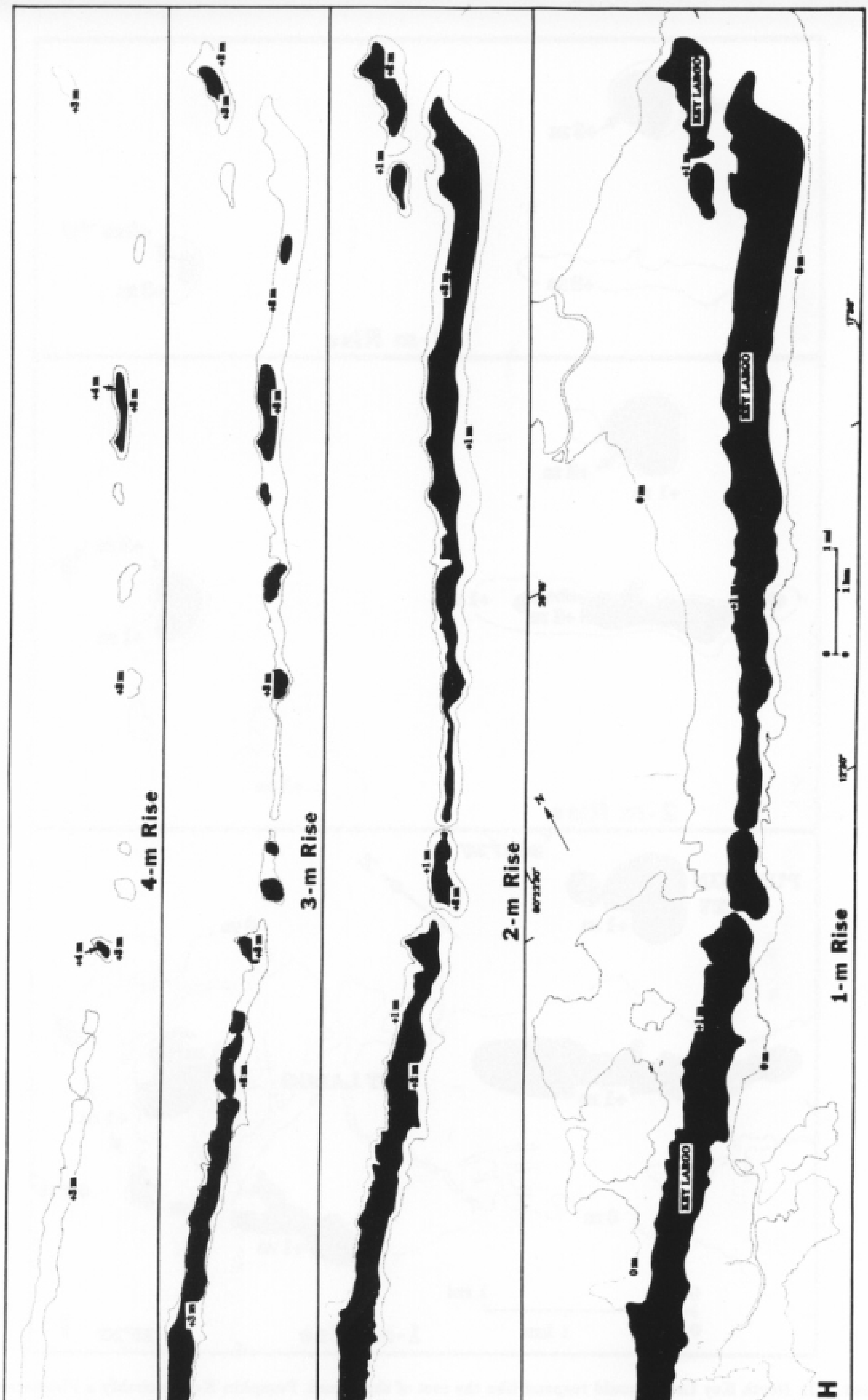

Figure 4 Cont. (H). Middle Key Largo would be affected similarly to lower Key Largo, with drowning of most land occurring at a 1-m rise in sea level and gradual flooding thereafter. Two small islands would remain at a 4-m rise. Most of Key Largo appears to be a Pleistocene barrier reef.

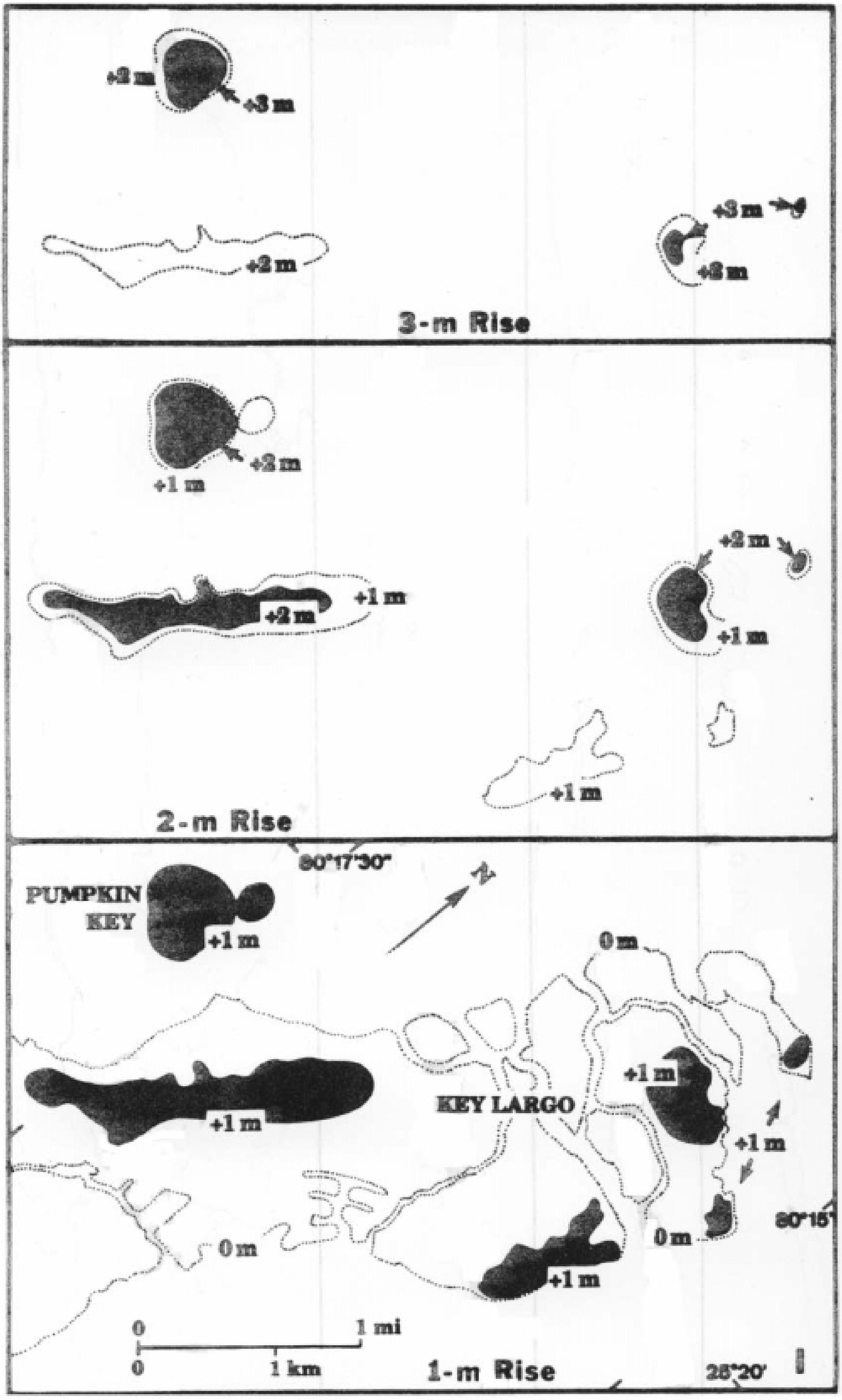

Figure 4 Cont. (I). North Key Largo would respond like the rest of the island. Pumpkin Key, probably a Pleistocene patch reef, would flood gradually, becoming completely inundated with a sea-level rise of >3 m.

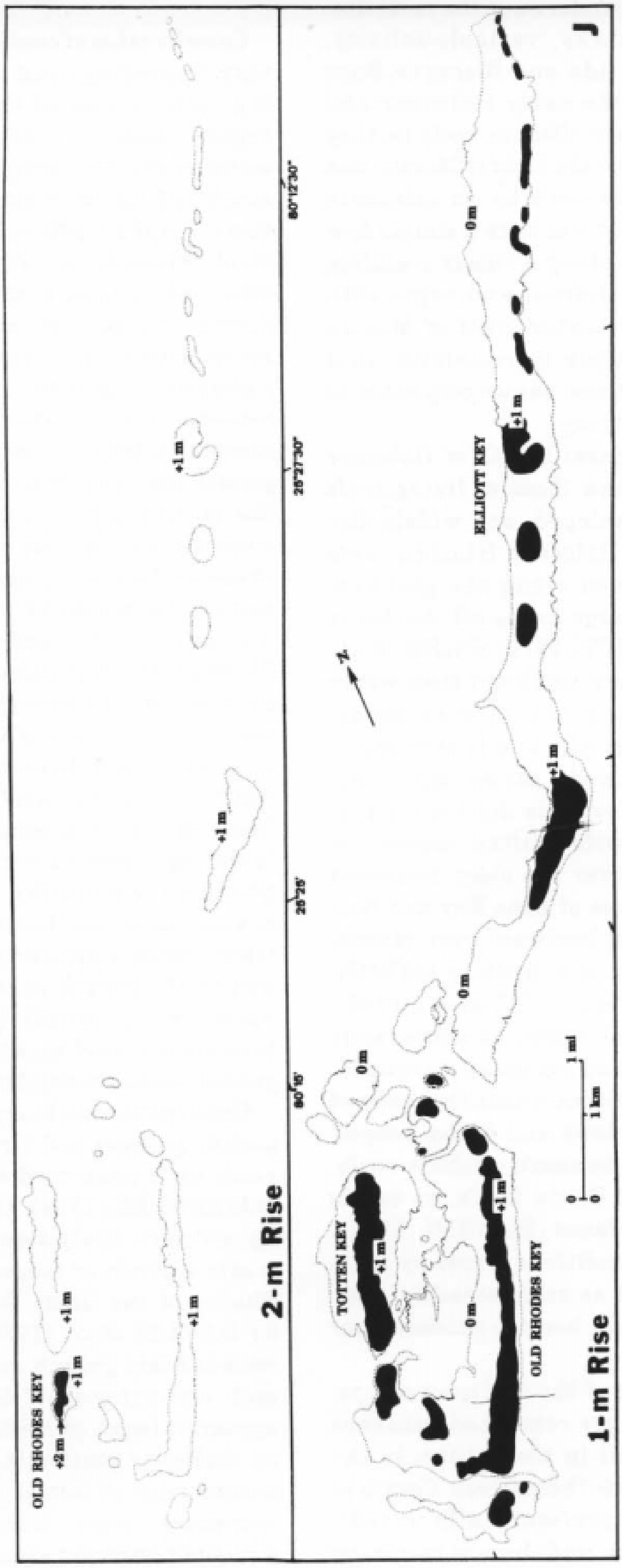

Figure 4 Cont. (J). Elliott Key and other islands forming the northern portion of the Florida Keys would flood rapidly in a 1-m sea-level rise, forming numerous irregularly shaped islands. A 2-m rise would drown them, leaving a single elongate feature at Old Rhodes Key.

rose during the last 8 ka BP. Circulation, controlled by topography, underwent the most dramatic change. The murky, variable-salinity, shallow waters of Florida and Biscayne Bays did not exist during the early Holocene and therefore did not impact offshore reefs as they do today, and water from the Gulf of Mexico was prevented access to the reefs by an extensive land barrier. Thus, what was once a simple flow of clear oceanic water along a linear coastline now involves complex diurnal exchanges with inimical inshore and turbid Gulf of Mexico waters through multiple intra-island tidal passes. Reefs opposite these passes responded to the adverse influx by dying.

Distribution and general health of Holocene reefs were different than those of living reefs today. Thick, well-developed, and widely distributed remnants of Holocene fringing reefs indicate they flourished along the platform margin and covered large areas off the lower and upper Keys (LIGHTY, 1977; SHINN *et al.*, 1989). Water depths were shallower than where their skeletal remains are located today. Today's reefs, less healthy and restricted to areas off the larger islands, cannot match the vitality, luxuriance, or wide distribution of those reefs. Living reefs shifted inshore as water became deeper over the older senescent reefs. Reefs such as those at Looe Key and Grecian Rocks backstepped landward over carbonate sand, as proven by core drilling (SHINN, 1980; SHINN *et al.*, 1981; LIDZ *et al.*, 1985). Large emergent areas of limestone temporarily became small islands and eventually drowned. Mangrove peat and soilstone crusts that formed in and on topographic lows and highs, respectively, became buried beneath offshore reefs, such as Alligator and Davis Reefs, as corals recruited to their surfaces (ROBBIN, 1984). Hence, the changing conditions forced by a rising sea were recorded as reefs steadily grew landward where possible, became senescent, or died.

The singular element of the reef tract ecosystem that has unerringly remained constant through time, and will in the future, is the underpinning of the reefs themselves. Corals in south Florida recruit preferentially to sediment-free bedrock highs, and there is no reason to believe they will not do so in the future.

Coral Growth

Growth rates of corals and the reefs they form vary depending upon many influences, including such factors as tectonic stability, energy regime, substrate and nutrient availability, water chemistry, temperature, and potentially confounding variables (development, pollution). Coral growth is intimately linked to sea level. Whereas reef *distribution* varies through time and is thus a spatial record of environmental change, individual corals and reefs preserve within their skeletons another kind of signature, a growth signature, imprinted as a response to environment. Corals deposit annual bands (HUDSON *et al.*, 1976) that indicate the growth rate and vitality of the coral. Similarly, the growth fabric or structural facies (framework species, detrital components) within a reef changes depending upon position of sea level and can be measured to produce a growth/vitality curve of the reef (DAVIES *et al.*, 1985). These growth signatures may not always be the same within the same coral or within the same reef. On the basis of these signatures, corals and reefs have been characterized by NEUMANN and MACINTYRE (1985) as being "keep-up" (growth equals rate of sea-level rise), "catch-up" (growth is rapid and independent of sea-level variation), or "give-up" (growth ceases upon sea-level rise). DAVIES *et al.* (1985) further divided catch-up reefs into categories: (1) growth is independent of sea-level variation, (2) growth is only able to catch up because sea level became stabilized, and (3) all growth commences after sea-level stabilization.

Generally, catch-up reefs are composed of prolific growers and form patch or bank barrier reefs on a protected shelf (NEUMANN and MACINTYRE, 1985). On the other hand, give-up reefs are likely slower growing species that create mounds or ridges on a broad deep shelf. Studies of the Great Barrier Reef of Australia by DAVIES *et al.* (1985) show that, although reefs initiate growth at about the same time in mid- and outer-shelf depths, the deeper reefs appear to begin immediate rapid growth. Reefs on shallower platforms, however, show a much slower rate of initial growth before the rate increases some time after colonization. Although different species of corals grow at different rates, the hardy reef-builders have been shown by BUDDEMEIER and SMITH (1988) to construct a reef at a best-estimate sustained maximum rate of 10 mm/yr. Using this rate and rates of sea-level rise over the past 50 and 100 years, they graphically show (their Figure 2) the relation between the rate of future sea-level rise and the responding rates of future reef growth.

Because reefs have been accumulating in these various fashions throughout geologic history, it seems unlikely their behavior would change in the event of a future sea-level rise. Future reefs would also unerringly record the appropriate spatial and growth signatures indicative of the particular environmental conditions in which they would have grown.

Future Shorelines and Implications of a Rising Sea

The use of postulated shorelines in a transgressing-sea scenario is a means by which we might better prepare for storm and tidal-surge conditions, in a time frame that is humanly relevant, and initiate long-term studies of developing coral reef and other nearshore ecosystems. This scenario may also serve as a model for predicting the locations of ancient buried reefs in the geologic record or future conditions in maritime regions elsewhere on the globe. It should be noted that the Pleistocene patch reefs, linear beachrock ridges, and oolite shoals that comprise the Florida Keys localized and shaped the islands as they exist today (HOFFMEISTER *et al.*, 1967; PERKINS, 1977; KINDINGER, 1986) and would similarly influence the shapes and orientations of the future reefs as they form on flooded terrain. The five cycles of marine transgression and regression identified by PERKINS (1977) in the Pleistocene record of Florida suggest there is little reason to believe the land will not flood again.

Figure 4A, E, and F show the highest elevations (5 + m) are located on Key West in the lower Keys, Lignum Vitae in the middle Keys, and on Windley and Plantation Keys in the upper Keys. Little more than 5 m of sea-level rise would therefore be required to eliminate all vestiges of land in the Florida Keys. Because much of the area shown as "land" on the 0- to + 1-m maps is mangrove swamps and intertidal mud flats already under water at high tide, 1 m of sea-level rise would drown these extensive areas of low elevation around Sugarloaf, Big Pine, and No Name Keys in the lower Keys; all of the middle Keys except Lignum Vitae; more than half of Key Largo; and all of the remaining reef tract to the north. Hurricanes temporarily raise sea level in the Keys by twice this amount (BALL *et al.*, 1967). Unlike the rapidly drowned islands of the lower and most of the middle Keys, Lignum Vitae in the middle Keys and most of the upper Keys would become submerged more gradually after the initial 1-m rise. Throughout the reef tract, numerous smaller islands would form. As in the past, corals probably would not grow opposite large tidal passes because of unsuitable conditions.

If the sea does not rise too quickly, rapidly growing corals would recruit to shallow, clear water and would become more abundant on progressively inundated reef flats. Communities protected from destructive waves and heavy sedimentation would accelerate their growth to match the rate of sea-level rise, up to a maximum rate of 10 mm/yr (BUDDEMEIER and SMITH, 1988). If the rate of sea-level rise exceeds this amount, the reef communities would lag behind and growth rates would further diminish as they become progressively submerged. The seaward portions of reef flats would eventually be subjected to progressively more destructive wave action, rendering reef growth there negligible.

Offshore reefs would die, while nearshore reefs would backstep. Increasing numbers of offshore senescent reefs would develop and temperature-sensitive reef-framework-building corals would decline as reefs migrated shoreward and the shoreline northward. Onshore topographic highs would become sites of future rocky islands, as were their predecessors, until all land in the area of the Keys flooded. The outer reefs might then shift as far "inland" as the Keys themselves and become established on the newly submerged calcrete-coated limestone as they did during the Pleistocene, if sea level does not rise too rapidly. If reef development at the shelf break should keep pace with the rising sea, however, the restricting influence of the reefs and margin sand shoals might cause the Keys to become encased in the muddy sediments being deposited around them today (ENOS, 1977). Although the Everglades shoreline is exceptionally irregular with hundreds of thousands of riverlets, inlets, and islands (particularly in the area along the southwest coast known as the Ten Thousand Islands), the Everglades, a vast, relatively flat, low-lying expanse of wetland, would rapidly and uniformly drown with little rise in the sea, as it had during the Pleistocene (PERKINS, 1977), and its migrating shoreline would become much less fragmented.

Slower growing corals not constrained by light, hard substrate, and position of the sea surface would become more abundant. Once below critical growth depth, however, (critical depth varies depending upon water quality and species of coral), reefs and reef flats would no longer keep pace with the rising sea and would become drowned give-up reefs like the present relict Holocene bank margin reefs. With continued rise and eventual drowning of the Keys, greater wave energy would impact Florida Bay. The mud banks and mud islands of the bay would be exposed to increased wave energy, particularly during periods of high tides and storms, as distance from land, degree of fetch, and lack of barriers increased. Fine-grained sediment would be transported to deeper waters off the shelf. The near absence of fine-grained limestones in the Pleistocene record of this region suggests this scenario has occurred before: modern lime mud accumulations are much thicker than any lime mud deposits in the Pleistocene section (SHINN *et al.*, 1989).

Whether the Miami Oolite and Key West Oolite areas would become coral reefs, or whether ooid shoals would once again form there is unknown. Unlike the Florida Keys, however, Key Biscayne and the islands of Miami Beach to the north are composed of uncemented quartzose carbonate sand that forms the Atlantic Coastal Ridge. These sands are likely to be reworked and probably would not provide suitable substrate for coral growth.

If local relative sea level continues to rise at its present rate of 38 cm/100 yrs, the half-meter mark would be reached in the lifetime of our great-grandchildren, 1 m would be attained in approximately 260 years, 2 m in 520 years, and 3 m in 780 years (Figure 5). The time differential would be significantly shortened if subsidence and acceleration of rate were to become factors. A rise of 1 m would not only inundate large areas of land and cause saltwater intrusion into freshwater aquifers, but would also make higher areas more susceptible to catastrophic destruction by hurricanes. Add to this rise a storm-surge effect of 2 m or more and the pending crisis is clear. Indeed, the global climate change scenario (of greenhouse warming) is generally accepted at the present time and suggests that hurricane activity will be more frequent and of greater intensity than previously experienced. Storm-surge, whether generated by hurricanes, subsea earthquakes, or other natural forces, is of exceptional significance to low-lying areas. The Florida Keys is only one such area. In terms of our already eroding shorelines and vanishing wetlands, the effects of rising sea level, regardless of rate, may well be felt in south Florida within the next 100 years.

SUMMARY

The thick limestone that underlies south Florida has undergone neither tectonic deformation nor significant erosion during the past 15 ka BP. This stability permits delineation of paleoshorelines as they existed before and within the last 8 ka BP by correlating local former sea levels with topographic contours. The positions and corresponding ages of shorelines between 8 and 2 ka BP are reasonably accurate because of the relatively precise correlative sea-level data for the area. The data are based on radiocarbon dates of peats, calcrete, and corals from the length of the reef tract and, in some cases, from beneath the reef itself.

By approximately 8 ka BP, sea level had risen from a lowstand of >100 m to at least 8.5 m below present level. At approximately 6 ka BP, the seastand against the Florida reef tract was at 5.7 m; at 4 ka BP, 2.8 m; and at 2 ka BP, sea level was 0.5 m lower than today. Data from the past 8 ka BP indicate that sea level has risen an average of 1.1 m/1 ka BP in the Florida Keys.

Although the magnitude of future global sea-level rise is a matter of conjecture, a continued rise is highly probable and may occur at an accelerated rate. Most of the Florida Keys would flood in a rise of 1 to 2 m within 260 to 520 years, if sea level continues rising at its present rate. A rise of 4.6 m would submerge all but the smallest remnants of the Keys and probably would create and shift shelfward conditions favorable for renewed growth of a >160-

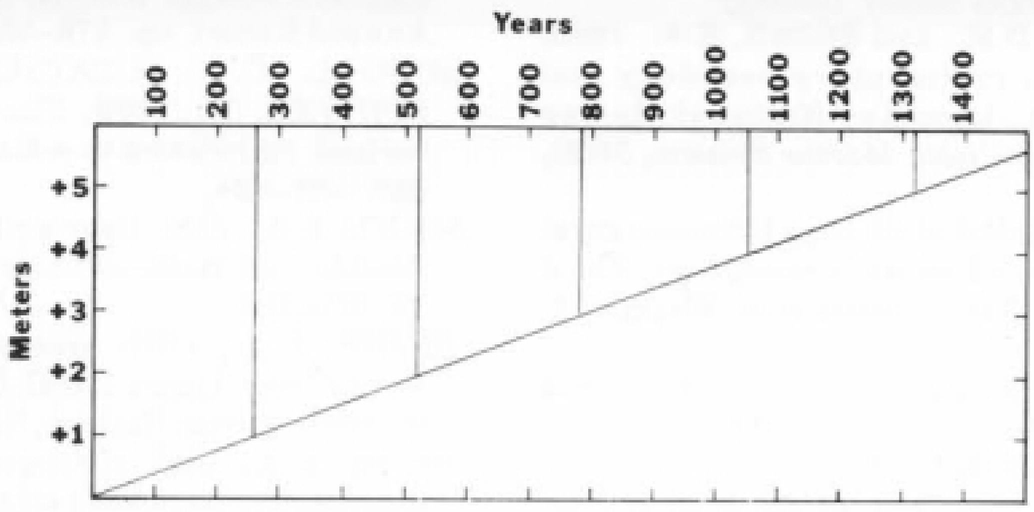

Figure 5. Chart showing future time in relation to projected sea-level rise (diagonal) at the current rate (38 cm/100 yrs) for Key West, Florida, assuming no subsidence. Vertical lines indicate 1-m intervals.

km-long reef tract. A rise of a little over 5 m would erase all vestiges of land from the area.

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□ RESUMEN □
Los lechos de roca caliza porosa, la fina cubierta sedimentaria y la estabilidad de la plataforma de Florida durante los últimos 15 *ka BP) oriveen una excepcionalmente apropiada situación para la reconstrucción de las paleolíneas de costa y la proyección hacia tierra de las futuras líneas de costa en un escenario de nivel del mar ascendente. Las paleo-líneas de costa correspondientes a 8, 6, 4 y 2 ka BP muestran que (1) una serie de islas emergían a lo largo de la plataforma exterior; (2) una clara depresión, llamada Hawk Channel, separaba las islas exteriores de la costa; (3) los cayos inferiores se inundaron primero y a mayor velocidad que el resto de los cayos, y (4) la Bahía de Florida y los pasos mareales a través de los cayos medios hacia la bahía se desarrollaron hace 4 ka BP. Durante el Cuaternario, las zonas elevadas fueron localizaciones preferenciales para el crecimiento del coral. Bañados por las claras aguas oceánicas, los arrecifes se desarrollaron en las márgenes de la plataforma y fueron desplazados gradualmente hacia costas de roca más cercanas a la costa. Una vez inundada la plataforma, la calidad del agua se deterioró y disminuyó el crecimiento de los arrecifes. La proyección de futuras líneas de costa sobre la tierra actual muestra que la mayor parte de la tierra firme que forma los cayos de Florida sería inundada por un ascenso del nivel del mar de 1 a 2 m y que un ascenso de algo más de 5 m sumergiría toda la tierra actual. Los arrecifes exteriors morirían mientras que los arrecifes costeros se moverían hacia tierra a medida que la línea principal de costa emigrara hacia el Norte. Las elevaciones terrestres actuales se transformarían en numerosas islas pequeñas a medida que se inundaran los cayos hasta que todos quedaran sumergidos. Las partes altas sumergidas serían entonces lugares preferecíales para el crecimiento del coral hasta que la calidad del agua o la profundidad excedieran el óptimo para la supervivencia.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ RÉSUMÉ □
La plateforme continentale de Floride est tectoniquement stable depuis 15000 ans BP. Par son substrat constitué de calcaires poreux recouverts d'une fine couche sédimentaire, elle est exceptionnellement favorable à la reconstitution de paléo-rivages et à la délimitation de rivages futurs dans un scénario de transgression marine. Les anciens rivages à 8, 6, 4 et 2000 BP montrent que: 1°) une série d'îlots calcaires, aujourd'hui submergés, répartisale long de la plateforme externese forma; 2°) un sillon distinct, le Hawk Channel, sépara les îles externes du rivage; 3°) les Cayes de Floride inférieurs furent submergés plus tôt et plus rapidement que le reste des Cayes; et 4°) le Golfe de Floride et les passages de marée faisant communiquer les Cayes centraux avec le golfe se développèrent au cours des 4000 dernières années. Au cours du Quaternaire, les hauts fonds sont des sites où se développent avec préférence les coraux qui, baignant dans les eaux claires de l'océan, prospèrent. Lorsque le niveau de la mer s'élève, des récifs se développent sur les marges de la plateforme et se déplacent peu à peu vers des positions situées sur les hauts fonds rocheux plus proches du rivage. sur la plateforme submergée, la qualité de l'eau se détériore et la croîssance des coraux décline. Si on extrapole de futurs rivages transgressifs á terre, on voit que la plupart des terres formant les cayes seraient submergées par une hausse de 1 à 2 m du niveau de la mer, et totalement englouties par une montée d'à piene 5 m. Les coraux situés au large mourraient, alors que ceux qui serainent situés plus près du rivage migreraient vers le Nord. Durant la trangression, les hauts fonds plus proches de la terre deviendraient une multitude de petits îlots, puis disparaîtraient tous. Ces hauts fonds submergés deviendraient alors des sites favorables à la croissance du corail, jusq'à ce que la qualité de l'eau et la profondeur dépasse l'optimum de survie.—*Catherine Bressolier-Bousquet, Géomorphologie EPHE, Montrouge, France.*

□ ZUSAMMENFASSUNG □
Der Untergrund aus durchlässigem Kalk, eine dünne Sedimentdecke und die tektonische Stabilität der Florida-Plattform während der letzten 15.000 Jahre bieten außerordentlich günstige Möglichkeiten zur Rekonstruktion früherer Küstenlinien und der Projektion künftiger Küstenlinien bei einem Szenario eines Meeresspiegelanstiegs. Alte Küstenlinien für die Zustände vor 8000, 6000, 4000 und 2000 Jahren zeigen, daß (1) zunächst sich eine Serie von Kalkinseln bildete, die dann entlang der äußeren Plattform ertrunken sind, (2) ein deutlicher Kanal (Hawk Channel) die äußeren Inseln von der Küste getrennt hat, (3) die niedrigen Keys früher und rascher uberflutet wurden als die übrigen und daß (4) die Florida Bay und die Gezeitendurchlässe der mittleren Keys in die Bucht sich erst in den letzten 4000 Jahren entwickelt haben. Während des Quartärs waren die topographischen Hochlagen bevorzugte Stellen des Korallenwachstums, die sie im klaren ozeanischen Wasser am Rande der Plattform vorfanden. Als der Meeresspiegel anstieg, entwickelten sich Riffe auf dem Rand der Plattform und allmählich auf den Felsaufragungen zum Festland hin. Da damit die Klarheit und Qualität des Wassers abnahm, entwickelten sich auch die Riffe weniger üppig. Eine Projektion zukünftiger Küstenlinien belegt, daß das meiste Land der Florida Keys bereits bei einem Meeresspiegelanstieg von 1–2 m überflutet und bei wenig mehr als 5 m alles ertrinken würde. Die äußersten Riffe würden absterben, während sich die küstennahen Riffe mit dem Wandern der Küsten landwärts vorschöben. Leichte Erhebungen auf dem Festland würden vor einer endgültigen Überflutung zunächst in zahlreiche Inseln verwandelt, die den heutigen Keys ähnlich sind. Die ertrunkenen Aufragungen würden anschließend bevorzugte Wachstumsstellen für Korallenriffe werden, bis die wasserqualität und die Riffe das Optimum für ihre entwicklung überschritten hätten.—*Dieter Kelletat, Essen, FRG.*